UCRL-52841, Volume 1

Energy storage systems for automobile propulsion: 1979 study

Volume 1
Overview and findings

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December 15, 1979

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ENERGY STORAGE SYSTEMS FOR AUTOMOBILE PROPULSION

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VOLUME 1

Page 49 - Substitute <u>enclosed</u> Table 14 for the one in report.

Page 76 - The dates are reversed on the tic mark example. They should read as follows:

1990 - 2000 1985 - 1990 1980 - 1985

Page 70 - 75 - Fig. 20 - Fig. 31 - The values plotted for the FeTi - ICE and Dual Hydride - ICE are incorrect in some cases. Refer to Vol. 2, Table 3 - 27, Page 3 - 66 through Table 3 - 32, Page 3 - 71.

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Prepared for Division of Energy Storage Systems Technology, U.S. Department of Energy

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PREFACE

This report presents the results of a study to investigate the suitability of energy storage systems for automotive propulsion, sponsored by the Technical and Economic Analysis Subprogram of the Division of Energy Storage Systems of the U.S. Department of Energy. The study was initiated in late FY 1976; work through FY 1979 is described in three two-volume publications of which this is the first of two volumes written following the study effort of FY 1979. This 1979 Volume 1 will summarize the total three year effort.

This study has been managed by Ervin Behrin and Hugh Forsberg, both of Lawrence Livermore Laboratory, as part of the Transportation Systems Research Program, which is directed by Lawrence G. O'Connell. A comprehensive listing of contributing organizations and individuals are given in the Acknowledgements at the end of this volume.

SUMMARY

Over the past three years we have performed a technical and cost analysis of energy-storage devices and propulsion systems for automobiles. Our goal has been to determine which devices and propulsion systems are capable of providing credible alternatives to current automotive propulsion systems between now and about the year 2000. This report, Volume 1: Overview and Findings, summarizes the three-year effort and includes much of the material presented in the 1977 and 1978 Volume 1 reports. The 1979 Volume 2 contains the details of only the FY 1979 work; the two previous Volume 2 reports should be consulted for the details of the study in those years. This year there is also a Volume 3 of the Study. This volume was produced at the request of the sponsor and contains a detailed analysis of Battery/Flywheel Electric Vehicles Using Advanced Batteries. It is in effect an appendix to Volume 2, published under separate cover, and will therefore not be considered as a separate entity in the following discussions.

This three-year study was performed as a multilaboratory project that also involved a number of industrial concerns, universities, and consultants, and was managed by the Transportation Systems Research Program at Lawrence Livermore Laboratory. Study Panels examined electrochemical, mechanical, and chemical/thermal storage devices and selected the most promising ones. The Panels then identified the research and development tasks necessary for successful development, determined the likelihood of overcoming technical barriers, and assessed the probable performance characteristics of future production devices. The characteristics sought for each device were specific energy and specific peak power. For batteries, the relationships between short-term specific power, specific energy, and total system energy capacity, were also determined. Since projected characteristics of future storage devices are uncertain, decision-analysis techniques were used to project values both as a function of the date of prototype availability and the level of optimism of the projection. Costs of the storage devices were also forecast.

From a large number of candidate storage devices, the Study Panels indicated the most promising devices, varying from 14 to 16 systems from year to year, for detailed evaluations. The Panels assessed the research and development tasks necessary for successful development of each device, the likelihood of the technical barriers being overcome, and projected both the probable and most-optimistic characteristics of future production devices, their dates of availability as preproduction prototypes, and cost. The Automotive End-Use Panel evaluated and compared them as complete automotive propulsion systems.

The procedure used was as follows:

- Five standard vehicle sizes representative of the future automobile population were defined. These ranged from a two-passenger, minimum-payload vehicle to a multipurpose vehicle intended as a composite of today's vans, small trucks, and luxury sedans.

- Four standard vehicle-performance levels (in terms of the peak-power-to-mass ratio and range) were also defined: (1) performance equivalent to today's internal-combustion-engine (ICE) automobiles, (2) performance needed for limited-range urban vehicles, (3) performance intermediate between the two, and (4) a minimum-performance level.

- The physical characteristics of the representative vehicles at each of the performance levels, assuming an ICE power system, were then specified and constituted the baseline for subsequent comparisons of energy-storage propulsion systems.

- Propulsion systems and vehicles incorporating the energy-storage devices recommended by the study panels were designed by computer modeling at various vehicle sizes, performance levels, time frames, and degrees of optimism. These vehicles included all-battery electrics, flywheel-boosted battery electrics, ICE/electric hybrids, hydrogen-fueled ICE-powered vehicles, hydrogen fuel-cell electrics, the dual-fueled hybrid (a battery/flywheel electric with a small ICE for hybrid range extension), and others.

- The mass, size, energy use, and cost of the energy-storage vehicles were then used as a measure of the suitability of the energy-storage propulsion systems in those types of vehicles in the time periods considered.

In the 1979 Study, for some systems this analysis has been expanded to project a determination of vehicle mass vs range, at fixed power-to-mass ratio.

Other factors have been added to the characterizations later in the study, but some evaluations are not yet complete. These factors include:

- Examination of possible market penetration of ESV under noncrisis conditions.
- Examination of the possible national energy impact of any major use of energy-storage vehicles (ESV).
- Identification of ESV combinations that can satisfy consumer mobility needs and national energy goals for transportation. Storage device and propulsion systems are based on the technical and cost phase of the study, and also consider the manufacturing and service infrastructure requirements.
- Development of a methodology to examine the effects of various political and economic policies on the penetration of ESV into the national transportation scene and its effect on energy use.
- Definition and evaluation of the manufacturing and service infrastructure changes that would accompany widespread shifting to selected ESVs from the current gasoline- and diesel-fueled automobiles.

As a result of this three-year study, the following conclusions were drawn:

- Automotive energy-storage propulsion systems can be developed for various performance levels from general-purpose vehicles (ICE equivalent), such as dual-fueled hybrids, power-leveling hybrids, and hydrogen systems, to specific mission vehicles, particularly battery/flywheel electrics and all-battery electrics.
- No secondary battery system studied can be projected as first choice for development given the present state of the art and the uncertainties of future battery characteristics. Rapid refueling by battery exchange, the only way for secondary-battery EV to meet general purpose capability, does not appear to be feasible for general-use vehicles.
- All advanced energy-storage devices and vehicles are high risk developments.

- Near-term EVs are expected to achieve only minimum and limited performance.

- Most ESVs will weigh more and cost more than their ICE equivalents. The cost differential will decrease with time.

- If ESV performance is reduced, then these automobiles can be more cost competitive with today's ICE vehicles.

- The Pb/acid battery system is projected as having the lowest cost for minimum-performance EVs and for the dual-fueled hybrid vehicle (DFHV) near-term, equivalent-performance level. In later time periods, the advanced batteries allow better performance and also project lower initial and life-cycle costs at the minimum and limited-performance levels.

- Flywheels or other mechanical-energy storage devices appear advantageous in higher performance EVs, where the cost of the battery capacity needed to reach the required acceleration levels may be much greater than the cost of the mechanical boost system.

- Hydrogen systems in general cost less than the all-battery EV's except at the minimum performance level. Liquid-hydrogen storage systems approach the ICE systems in initial cost at the equivalent-performance level, but have higher life-cycle costs.

- Dual-fueled hybrids are projected to provide vehicles of equivalent performance over all time periods, at costs comparable to limited-performance EV. However, petroleum costs and availability could seriously affect the status of DFHV.

- Although the projections of performance and cost for the exploratory Al/air battery system have a high degree of uncertainty at this tiime, the specific energy and rapid refueling capability are expected to make it the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles.

- Factors such as safety, supply problems, and infrastructure impose serious problems on several systems including thermal-energy storage and hydrogen systems, especially the cryogenic liquid system.

ENERGY STORAGE SYSTEMS FOR AUTOMOBILE PROPULSION: 1979 STUDY

Volume I: Overview and Findings

ABSTRACT

We have performed a technical and cost analysis of energy-storage devices and propulsion systems for automobiles. Study Panels examined electrochemical, mechanical, and chemical/thermal storage devices, selected the most promising ones, and projected their characteristics into three time frames through 2000. The Automotive End-Use Panel modeled these devices and propulsion systems as vehicles of several sizes and performance levels and prepared comparative evaluations between systems and with projected baseline internal-combustion-engine vehicles.

INTRODUCTION

Conventional domestic and foreign sources of petroleum are limited in a period of increasing world consumption: future fuel shortages and dramatic price increases are inevitable. In the U.S. we rely almost exclusively on petroleum fuels for transportation. The automobile accounts for almost 75% of all petroleum used for transportation. Thus, without alternatives to petroleum-fueled automobiles, we will remain vulnerable to embargos and petroleum shortages.

In anticipation of these problems, the U.S. Energy Research and Development Administration initiated this study in 1976 to examine various energy-storage devices as possible alternatives to petroleum-fueled internal combustion engines (ICEs). The study covers three specific time periods: 1980 to 1985, 1985 to 1990, and 1990 to 2000, and includes an evaluation of the relative cost of the resultant automobiles and an indication of their impact on future petroleum demand.

OBJECTIVES

Other researchers and analysts have evaluated individual energy-storage devices and power systems, but it is difficult to find a common basis for comparison. Therefore we examined a wide range of energy-storage systems and evaluated the relative performance, weight, and cost of each, using standardized guidelines and procedures to facilitate comparison. Not only are we looking for the most promising devices, but we are also seeking the technical barriers to be overcome before these devices can be successfully developed and marketed. We are also seeking some indication of the national energy impact of energy-storage vehicles (ESVs), particularly with respect to petroleum demand reduction, under business-as-usual circumstances when petroleum is readily available. Later we identified ESV combinations that could satisfy consumer mobility needs and national energy goals for transportation. Finally, an evaluation was begun on the manufacturing and service infrastructure changes that would accompany any major shift from petroleum-fueled vehicles to ESVs.

STUDY ORGANIZATION

The study first reported its work through FY 1977. The work coninues as a multilaboratory effort managed by LLL. For FY 1978, the study team again drew personnel from four DOE laboratories and divided them into five panels. Four of the panels investigated energy-storage technologies and a fifth evaluated energy-storage power systems. The Electrochemical Panel, chaired by Argonne National Laboratory (ANL), examined batteries; the Mechanical Panel, chaired by Battelle Pacific Northwest Laboratory (BPNL), evaluated mechanical-energy storage devices; the Chemical/Thermal Panel from 1977 was split into two panels, the Chemical Panel, chaired by Brookhaven National Laboratory (BNL), examined hydrogen systems, while the Thermal Panel, chaired by ANL, evaluated this technology. The fifth panel was the Automotive End-Use Panel chaired by LLL. This panel investigated the suitability of energy-storage devices for future automotive propulsion. For FY 1979, the panel arrangement was modified only slightly. The Thermal Panel work was completed and the panel was disbanded. Two new areas of work were begun, designated as the Impact and Infrastructure tasks, but were not officially set up as panels.

REPORT ORGANIZATION

Each year's report is divided into two volumes. Volume 1 is a summary of the analytical work and the findings and conclusions drawn from the work done to date. Volume 2 is a detailed discussion of the tasks completed in the current fiscal year. The 1977 Study was published as UCRL 52303 and the 1978 Study as UCRL 52553.

ANALYTICAL APPROACH

PROCESS

We began the study in late FY 1976, classifying energy-storage devices as either electrochemical, mechanical, or chemical/thermal and establishing an investigative panel for each area.

Each Panel was given the task of assessing the probable performance characteristics of future energy-storage devices, determining the likelihood of overcoming technical barriers, and identifying the research and development tasks to be accomplished for successful development. This was done in various ways: through intensive literature searches, through interviews with leading developers, and through analytical evaluation of the storage devices from fundamental physical principles. The characteristics sought for each device were specific peak power and specific energy. With batteries, the relationship between specific power and specific energy was also required since they are related and are a function of the internal design of the battery. Over the three-year period of the study evaluation procedures were slightly modified, but basically the study continues as conceived.

The projected characteristics of future storage devices are uncertain and that degree of uncertainty is important. So, using decision-analysis techniques, these characteristics were defined not only as a function of time but also as a function of the likelihood of attainment. This latter parameter was characterized as simply Probable, meaning that it had reasonable expectation of being achieved, and Optimistic, which inferred the level of an unachievable upper limit.

It is difficult to predict the level of vehicle performance that will be acceptable in the future. And yet performance requirements bear heavily on the acceptability of energy-storage devices. For this reason an Automotive End-Use Panel established four performance criteria: (1) performance equivalent to that of today's internal combustion engine (ICE) automobiles, (2) performance needed for a limited-range urban vehicle, (3) performance intermediate between the two, and (4) a minimum usable performance level. These performance levels were defined in terms of both power-to-mass ratio (acceleration) and range with the acceleration capability maintained to the 80% discharge level of the batteries or other energy supply. This assured that safety of operation will not be degraded.* At the same time we defined five vehicle sizes representative of the future automobile population. With the 4 performance levels and the 5 standard vehicle sizes, we could define 20 distinct vehicles encompassing a wide spectrum of automobile types.

We designed ICE automobiles in each size/performance category and calculated their characteristics. These values constituted a baseline for comparison. Then, we conceptually replaced the ICE propulsion system of each vehicle with various energy-storage propulsion systems designed to the same vehicle performance. By calculating the resulting vehicle weight, size, energy use, and cost (as a function of the likelihood and the three time periods), we could evaluate the suitability of each energy-storage device and propulsion system in each type of vehicle.

The characteristics of each energy-storage automobile and each ICE automobile were calculated over SAE driving cycles by means of the LLL Vehicular Performance Model. Each energy-storage power system was also evaluated in terms of the technical barriers yet to be overcome.

The analysis was completed by bringing together all the resultant vehicle-system characteristics, costs, and technical barriers, which allowed us to compare various energy-storage devices and power systems with each other and their ICE counterparts.

LIMITATIONS

In examining the gamut of energy-storage devices and evaluating their performance, we had to establish the arbitrary standardizing procedures and performance categories described above. We made these as reasonable as possible, but we recognize that different procedures and categories might be used.

In a study of this scope and purpose, it was not possible to examine all the variations of each propulsion system. The results in any given case could probably be altered by design modifications. However, we do not expect that this would have a major effect on the study conclusions.

*In the last year of the study, the LLL Vehicular Performance Model was modified to project vehicle mass (low mass being a surrogate for desirability) as a function of vehicle range, at fixed power-to-mass ratios. It was felt that a high-acceleration, low-range vehicle might be more appealing as a commuter car.

No one can predict the future with absolute certainty. Our selection of technically promising devices and our forecasts of their characteristics are based on expert judgement and the present state of the art. Future discoveries or technical breakthroughs could significantly alter the projections.

This study limits its analysis to the time period ending about 2000. As the projected characteristics of future energy-storage devices and the resultant automotive propulsion systems have become more firmly established, the study has been extended into certain adjacent areas. The impact of these developments on the transportation markets and national energy picture, as modified by various national energy goals, has come under investigation. Changes in manufacturing and service infrastructure accompanying any major shift to energy-storage vehicles are under evaluation. Major components of energy-storage vehicles such as continuously variable transmissions (CVTs) have come under examination and the specialty energy-storage vehicles market, which currently includes golf carts, fork lifts, etc., were also surveyed. We felt it could be an important factor in the future development of nonpetroleum-fueled vehicles by providing a market for some of the storage devices under development.

ENERGY-STORAGE DEVICES

ELECTROCHEMICAL DEVICES

There are a large number of potential candidate electrochemical systems for electric vehicle applications. An extensive search of the open literature and other sources resulted in the listing in Table 1. Because of the difficulty of comparative evaluation of candidate systems in different stages of technological maturity, the systems were divided into three groups, Engineering, Advanced, and Exploratory stages of development.

Some of the battery candidates were ruled out at an early stage because of requirements of large quantities of rare and expensive materials, grossly inadequate electrical performance, or very low energy efficiency for the electric-vehicle application. After three years of evaluation, the Electrochemical panel has identified six battery systems in the engineering and advanced stage of development as most promising and likely to become a commercial reality by the turn of the century.

TABLE 1. Original candidate battery systems.

Engineering stage	Advanced stage	Exploratory stage
Lead/acid	Iron/air	Aluminum/air
Nickel/iron	Lithium/chlorine	Calcium/air
Nickel/zinc	Lithium/iron sulfide	Calcium/copper flouride
Nickel/hydrogen	Nickel/cobalt	Calcium/sulfur
	Nickel/hydrogen	Iron/oxygen
	Silver/hydrogen	Lithium/air
	Sodium/sulfur (ceramic electrolyte)	Lithium/copper sulfide
	Zinc/air	Lithium/selenium
	Zinc/bromine	Lithium/titanium disulfide
	Zinc/chlorine	Manganese/lead
		Manganese/zinc
		Redox systems
		Sodium/air
		Sodium/metal chloride
		Sodium/sulfur (glass electrolyte)
		Zinc/oxygen

- Ni/Zn, Pb/acid, and Ni/Fe in the engineering stage of development.
- Zn/Cl_2, $LiAl/FeS_x$, and Na/S (cer) in the advanced stage of development.

In addition, the panel determined that several of the exploratory systems show particular promise for future automotive application, especially the Na/S (glass) and Al/air systems.

Evaluation Methodology

Forecasting and characterizing complex battery technologies is difficult at best. The Electrochemical panel was faced with a number of candidate battery systems, each with loyal advocates, insisting that their battery is clearly the best and that successful development and commercialization is nearly certain. In reality, every one of the developments is a high-risk enterprise with difficult cost, cycle life, or electrical-performance barriers to overcome. The Electrochemical Panel developed an assessment technique based on Bayesian decision-analysis principles to cope with these problems.

The main objectives of the battery-system evaluation effort were to project the future system characteristics for vehicle-propulsion-system models by the Automotive End-Use panel and to assess the relative development risk. The major characteristics of interest were:

- Electrical performance
    - Specific energy
    - Volumetric energy density
    - Specific peak power at 80% discharge
    - Sustained-power capability
    - Relationship between specific peak power and specific energy
    - System size effects
- System cycle life
- Cost
- Safety
- Materials requirements/availability

Over the three years of this study, there were changes in the projected characteristics of the various systems because of ongoing R&D and testing programs. These data have been updated throughout the study. In addition there have been changes in the evaluation techniques, such as more sophisticated methods of optimizing the battery systems to meet the specific needs of the vehicle and performance requirements. The evaluations and projections below resulted from the most recent data and techniques.

Engineering and Advanced Batteries

The most recent projections developed by the Electrochemical Panel for the six systems included in the engineering and advanced categories are shown in Tables 2 and 3. The specific energy at the 3-h discharge rate ($E_{c/3}$) is used to generally characterize the total energy content. The 5-h discharge rate ($E_{c/5}$) is used during the End-Use Analysis in the process of obtaining the optimum battery design for a specific-use cycle. The short-term peak power at the 80% discharge level (P_{M80}) is a major factor in determining the vehicle-acceleration capability and thus its performance as mentioned earlier.

Table 4 lists some technical barriers that currently impede the development of the six battery systems for electric-vehicle application.

TABLE 2. Battery forecasts for engineering batteries.

Battery type	Time period[a]	Prob. level[b]	$E_{C/3}$,[c] Wh/kg	$E_{C/5}$,[c] Wh/kg	P_{M80},[d] W/kg
Pb/acid	1	Opt.	47	54	75
		Prob.	42	48	66
	2	Opt.	52	59	100
		Prob.	46	53	95
	3	Opt.	57	65	110
		Prob.	49	56	98
Ni/Fe	1	Opt.	60	64	130
		Prob.	55	59	102
	2	Opt.	70	75	143
		Prob.	60	64	112
	3	Opt.	80	85	157
		Prob.	65	70	130
Ni/Zn	1	Opt.	76	81	140
		Prob.	70	74	125
	2	Opt.	85	91	160
		Prob.	76	80	135
	3	Opt.	92	96	175
		Prob.	80	86	140

[a] 1--1980-1985, 2--1985-1990, 3--1990-2000.

[b] Optimistic or Probable.

[c] Specific energy at 3-h (5-h) discharge rate.

[d] Specific peak power when 80% discharged.

TABLE 3. Battery forecasts for advanced batteries.

Battery type	Time period[a]	Prob. level[b]	$E_{C/3}$, Wh/kg	$E_{C/5}$, Wh/kg	P_{M80}, W/kg
Na/S(cer)	2	Opt.	105	122	120
		Prob.	90	105	100
	3	Opt.	120	140	140
		Prob.	108	125	120
Zn/Cl_2	1	Opt.	100	105	120
		Prob.	90	95	95
	2	Opt.	112	118	135
		Prob.	98	104	115
	3	Opt.	120	130	150
		Prob.	105	111	120
Li/FeS_2	2	Opt.	120	140	125
		Prob.	110	128	115
	3	Opt.	140	155	150
		Prob.	120	140	130

a 1--1980-1985, 2--1985-1990, 3--1990-2000.

b Optimistic or Probable.

TABLE 4. Key technical Barriers.[a]

Advanced Pb/acid	Ni/Fe	Ni/Zn	Zn/Cl_2	$LiAl/FeS_x$	Na/S(cer)
Specific-energy Peak-power lifetime	Cost[b]	Lifetime[b] Cost	Volumetric energy Cost Lifetime Safety[b] System complexity	Specific energy Cost Lifetime[b] Materials corrosion Battery eng. Separator	Specific energy Volumetric energy Lifetime Materials corrosion Safety[b] Peak power Battery eng.
Probability of[c] overcoming all key barriers (estimated)					
0.25	0.5	0.35	0.25	0.25	0.15

[a] Only technical barriers with serious development difficulty are included.
[b] Denotes especially difficult technical barrier.
[c] Assumes intensive development until 1990.

Exploratory Battery Systems

Impressive advances have been made during the last year on the Na/S (glass) battery. Dow Chemical has demonstrated a metal-cased, hermetically-sealed, 40 Ah cell which they believe represents full-scale cell size for EV application. Table 5 describes this system.

The aluminum/air battery has also made good progress during the past 12 months, with demonstration of the cell chemistry and development of working cell stacks. An important advance has been the development of improved power capability that makes aluminum/air batteries a more suitable candidate for automotive propulsion. The principal problems relate to the chemical engineering of the system rather than the cell stack itself. The projected cost of

TABLE 5. Battery forecasts for Na/S batteries (glass).

Battery type	Time period[a]	Prob. level[b]	$E_{C/3}$, WH/kg	$E_{C/5}$, Wh/kg	P_{M80}, W/kg
Na/S(glass)	2	Opt.	118	120	200
		Prob.	112	114	180
	3	Opt.	125	127	250
		Prob.	118	120	200

[a]1--1980-1985, 2--1985-1990, 3--1990-2000.

future aluminum/air batteries has a high degree of uncertainty. However, the specific energy and rapid refueling capability are expected to make the aluminum/air battery the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles. This battery system is especially difficult to evaluate because of uncertain reprocessing costs and lack of experience with fully integrated battery systems.

MECHANICAL DEVICES

Early in the study the Mechanical Panel examined many mechanical-energy-storage devices that might be useful in automotive propulsion. These devices are well defined and their energy-storage characteristics can nearly always be evaluated on the basis of physical principles and materials properties.

Energy can be stored mechanically in solid or liquid springs (as potential energy), in moving mass (as kinetic energy), or in some combination of the two. Six types of mechanical-energy-storage devices were selected for evaluation during the study.

- Linear-elastic solids
- Elastomers
- Liquid springs
- Hydraulic accumulators
- Compressed air
- Flywheels

Theoretically, any of these devices can provide energy for vehicular propulsion, store energy for quick release when high power is required, or conserve energy that would normally be dissipated in braking. However, their practical usefulness is directly related to the strength-to-mass ratio of the materials used, i.e., the stored energy per unit system mass and volume. Another significant criterion for comparison is cost.

In linear-elastic solids, energy is stored as elastic strain energy. While ultimate gravimetric energy-storage densities of fiber composite materials may approach 6 Wh/kg, safety factors and configuration limitations reduce the useful value to under 2 Wh/kg.

Elastomers also store energy in the form of elastic strain. Elastomeric energy-storage materials have an average gravimetric energy-storage density of about 6 Wh/kg for a single cycle. However, after a number of cycles, this declines to about 2 Wh/kg.

The energy-storage density of compressed fluids depends on the strength of the container. Compressed liquids are used in some springs and shock absorbers and can generate extremely high power densities. However, their energy-storage capacity is very low. Gravimetric energy-storage densities, even with advanced fiber-composite pressure vessels, are less than 2 Wh/kg, and the extreme pressures required render this mode of energy-storage unsuitable for vehicular applications.

Hydraulic accumulators store mechanical energy by compressing a fixed precharged mass of gas in a compartmented pressure vessel. For a given pressure-vessel efficiency, the density of the stored energy depends on the thermodynamic cycle of the compressed gas. Ideally, an isobaric (constant-pressure) cycle would provide the highest attainable energy-storage density. Although some research has been conducted in this area, most hydraulic accumulators operate on a polytropic cycle, which with advanced fiber-composite pressure vessels could achieve gravimetric energy-storage densities approaching 5 Wh/kg.

Compressed air may be used to store energy if a source of waste heat is available to heat the air before it is expanded through a motor. The exhaust from a heat engine could be such a source. Since the receiver is the largest component in the system, it is desirable that the pressure be as high as practicable to improve the volumetric energy density. The majority of the energy recovered with this system is the heat energy recoverable from the engine exhaust, which is normally discarded. Thus the system is only practical under very limited circumstances.

Energy can also be stored in a rotating disk or ring. The gravimetric energy-storage density of disk or ring flywheels is a function of both the strength-to-mass ratio of the material and the configuration of the rotor. To reduce friction caused by air drag, the rotor must be enclosed in a vacuum. Thus seals are an important factor. Energy is further dissipated through friction in bearings. Gravimetric energy-storage densities of flywheel assemblies consisting of rotor, shaft, housing, and vacuum systems vary from 6 to 8 Wh/kg for state-of-the-art isotropic rotors to 30 to 40 Wh/kg projected for fiber-composite flywheels of the 1990-2000 time frame.

Only flywheels, compressed-air storage, and hydraulic accumulators seem to have practical application in automotive systems, and that not as primary sources of propulsion (because of low gravimetric energy density). Flywheel systems have marginal energy densities and continuously lose energy. However, they are good as power-boosting devices. Compressed-air storage requires a source of thermal energy, and it would have to be used in combination with a heat source. Hydraulic accumulators have very low energy densities, but could be useful in hybrid applications, since hydraulic components are well developed and reliable.

The study has not uncovered any major advances in basic flywheel technology since the 1977 Study. However, for automotive application the major use of this mechanical-energy storage is for power boosting and load leveling rather than as a sole energy source. The energy-storage requirements for these functions are a small fraction of what would be required if the flywheel system were used as a principal source of energy. Both the isotropic and the state-of-the-art fiber-composite type flywheel systems could be very useful devices for improving the performance of electric and hybrid vehicles. The choice will depend on their relative impact on the price, reliability, and safety of the vehicle. Extensive analysis of these factors indicates that although the specific energy of the fiber-composite flywheel appears to be much higher than that for isotropic flywheels (based on the strength of the composite in the direction of the fibers), the uncertainty in predicting their mechanical behavior at this time places them at a disadvantage. Given time and enough funding, the fiber-composite flywheel may reach a level of development that would remove these uncertainties.

During the study a considerable effort was spent on gaining an understanding of how test procedures can be developed to characterize the safety of flywheels, and analysis was continued on flywheel power-boosted EVs using carefully optimized battery designs. The results indicated that such systems can be highly effective as power boosters in certain automotive propulsion applications. It is also suggested that isotropic flywheels should receive developmental attention comparable to that devoted to the fiber composites.

Another mechanical device is the continuously variable transmission (CVT). Although it is not an energy-storage device, it is an important link in the ESV and hybrid-vehicle drive train is the Therefore we believe it is pertinent to survey the state of the art of that device.

Continuously Variable Transmissions

Transmissions with continuously variable ratios (CVT) have many uses in vehicles powered by energy-storage systems. For example, some type of CVT is a virtual neccessity in coupling an energy-storage flywheel to a vehicle's drive train. The energy efficiency of battery-powered cars can also be increased by the use of a CVT. With such equipment, the traction motor's best speed could be matched to a wide range of driving conditions. A CVT can also aid in achieving the best speed matching for regenerative braking.

Other potential uses for CVTs are in hybrid-vehicle power systems and in those powered by hydrogen. In short, every motor or engine has a regime of most-efficient speeds and torques and it requires a wide range of ratios to bring the best combination into play.

Possible advantages of the CVT for automobiles have been apparent to engineers for more than 80 years. Several makes of early-day passenger cars had traction drive CVTs with an infinite ratio range. Early CVTs, while reasonably efficient, lacked the durability required for high-powered engines. The hydrodynamic torque converter found widespread use as the infinitely variable element of automatic transmissions. But this is unfortunate because the torque converter is not very efficient at high ratios.

CVT industrial drives have also found many uses and many different types have been invented. Variable-ratio belt drives are efficient over a wide ratio range. Belt drives are also relatively inexpensive, but heretofore have been too bulky for use in standard automobiles. Recently a metallic V belt has been devised that could overcome this disadvantage.

Improved versions of traction drives may be ideal for high-speed applications such as flywheel or turbine couplings. Traction drives have a high mechanical efficiency.

Hydrostatic and electric drives have been applied to heavy off-road vehicles and to railroad locomotives. These are ideal for smoothly starting heavy loads, but thus far the efficiencies have been only moderate and the costs are high. They are compatible with energy-storage devices (hydraulic accumulators or electric batteries).

Still other CVTs embody a combination of working principles. Examples are the hydro-mechanical and electro-mechanical transmissions. Usually these are based on the geared differential in which the ratio between two shafts is adjusted by varying the speed of a hydraulic or electric biasing motor on a third shaft.

A lot of development engineering must be done on many of these transmissions before all criteria important to energy-storage propulsion can be met. In many cases the efficiency needs to be improved, particularly at part load and at high ratios. Because many of the commercially available units were aimed at industrial uses, mass and bulk must be reduced while retaining low manufacturing costs.

Many of the visualized uses for CVTs will require intelligent control systems and much effort will be needed to develop both the control technology (at reasonable prices) and the underlying use philosophies.

CHEMICAL AND THERMAL DEVICES

Chemical storage systems for our purposes are systems using hydrogen. They differ from conventional liquid-fuel systems in that the fuel is stored in a chemical compound or in a liquid form and must be liberated by some process before it can be burned. Thermal storage devices store energy in the form of heat, which can be used to drive a Stirling engine or some other external heat engine.

The chemical/thermal systems considered in the study rely on the following reactions:

Liquid hydrogen + heat $\rightarrow$ H_2 gas

Iron titanium hydride + heat $\rightarrow$ H_2 gas

Magnesium alloy hydride + heat $\rightarrow$ H_2 gas

Ammonia + heat + catalyst $\rightarrow$ H_2 gas + N_2 gas

Methanol + heat + catalyst $\rightarrow$ H_2 gas + CO_2 gas

Methylcyclohexane + heat + catalyst $\rightarrow$ H_2 gas + toluene

Lithium hydride + water $\rightarrow$ H_2 gas + lithium hydroxide + heat

Thermal energy: liquid LiF $\rightarrow$ solid LiF + heat

The liquid hydrogen, iron titanium hydride, magnesium-alloy hydride, ammonia, methanol, and thermal storage systems are directly rechargeable. The lithium hydride and methylcyclohexane systems require recycling of the carrier material in a processing plant.

Liquid hydrogen systems store the hydrogen at its boiling temperature ($-252^{\circ}C$) in insulated tanks. It is then pumped through a vaporizer and used as a gaseous fuel. The hydrogen reservoir must be designed to minimize losses through boiloff and to lessen heat leakage into the storage tank. The safety aspects of liquid hydrogen systems are also of considerable concern.

Iron titanium hydride ($FeTiH_x$) serves as a hydrogen carrier at ordinary temperatures and moderate pressures. Application of heat will cause dehydriding and release of hydrogen, while cooling will cause absorption of hydrogen (i.e., refueling). Design optimization of the reservoir for the hydride bed is an ongoing effort in a number of organizations.

The hydride of magnesium/nickel (10 wt%) also stores hydrogen reversibly. Since the alloy density is considerably less than that of $FeTiH_x$ and its hydrogen content much higher (5.5 wt%), it offers a potential increase in specific energy. Magnesium/nickel hydride requires more heat for release of hydrogen than does $FeTiH_x$. If hydrogen must be burned to supply the extra heat, there would be a corresponding reduction in specific energy.

The thermal storage system evaluated used a molten salt (lithium fluoride) and a liquid-sodium heat pipe to transfer the thermal energy to a heat engine (Stirling engine). Because of the cost and difficulty of recharging the system, the problems attending the development of the Stirling engine, and the hazards of the molten salt/liquid metal transfer pipe, the thermal system was dropped from the study after the second year.

The hydrogen systems having fewer technical barriers were selected for continued evaluation and analysis by the Automotive End-Use Panel. These were the liquid (cryogenic) hydrogen system and the systems using titanium and magnesium alloy hydrides. During the third year of the study a new hydrogen-storage technique was examined and evaluated. This method uses a bed of hollow glass microspheres filled with hydrogen at high pressure and discharged in a controlled fashion for the hydrogen supply. The particular glass used in the microspheres has a high permeability to hydrogen at high temperatures and low permeability at low temperatures. Thus they can be filled in an autoclave and the rate of hydrogen release can be easily controlled by temperature.

Another addition to the study was a system using a hydrogen fuel cell coupled with a minimum-capacity Ni/Zn battery-power booster as an all-electric automotive propulsion system.

Summaries of the projected characteristics of the hydrogen-storage devices are given in Table 6.

TABLE 6. Current hydrogen-storage-device projections. Note: Heat content values have been converted to their mechanical equivalent using 30% efficiency.

Storage devices	Probability	Specific energy Wh/kg 1980-1985	Specific energy Wh/kg 1985-1990	Specific energy Wh/kg 1990-2000	Specific peak power (80% discharge) W/kg 1980-1985	Specific peak power (80% discharge) W/kg 1985-1990	Specific peak power (80% discharge) W/kg 1990-2000
Liquid H_2	Prob.	675	1080	1680	a	a	a
	Opt.	1080	1680	1680	a	a	a
$FeTiH_x$	Prob.	84	90	96	1100	1230	1320
	Opt.	99	105	114	1320	1440	1560
MgH_x	Prob.	105	144	165	870	1230	1380
	Opt.	195	201	207	1650	1680	1740
Microcavity	Opt.	--	381	--	--	570	--

[a] In this case the peak-power capacity is determined by the design of the heat engine.

AUTOMOTIVE END-USE ANALYSIS

REPRESENTATIVE VEHICLES AND PERFORMANCE LEVELS

Vehicle parameters and performance requirements determine propulsion-system requirements. Therefore before evaluating the various energy-storage power systems and comparing them with existing power systems, we had to characterize the automobiles in which they will operate. We thus defined four vehicle sizes, which we believe to be representative. They are described by curb mass and as a function of various performance levels for three time periods and two levels of probability as shown in Table 7. The specific performance levels are described below. They are also given in Fig. 1 for a size comparison. During the period of the study we determined that no significant changes were made in standard automobiles.

The two-passenger vehicle was included in recognition of the trend toward lightweight urban vehicles. The four- and five-passenger size classifications conform to the "mass conscious" configurations of the Federal Energy Resources Council Task Force's Motor Vehicle Study. The multipurpose vehicle is a composite of a number of present-day vehicles, including vans, small trucks, and luxury sedans.

The payload and frontal area of the four representative vehicles are given in Table 8. The vehicles were selected to bracket the spectrum of passenger vehicles expected to be on the road in the future.

In view of the uncertainty of the exact performance levels that will be demanded of future automobiles, we established four standard levels of performance to use in our comparisons of energy-storage and heat-engine power systems:

- ICE-equivalent performance
- Intermediate performance
- Limited performance
- Minimum performance

An ICE-equivalent vehicle has a power-to-mass ratio of 0.049 kW/kg (0.03 hp/lb) and a range of 400 km (250 mi) as measured over the SAE J227a(D) driving cycle. The storage system must be capable of being refueled, recharged, or exchanged in less than 15 min. This performance level is typical of general-purpose ICE vehicles.

TABLE 7. Baseline vehicle specifications.

Vehicle type	Prob. level	Time period[a]	Curb mass kg (lb) Performance levels Min.	Limited	Inter.	Equiv.
2 Pass.	Prob.	1,2,3	392(864)	427(942)	460(1014)	544(1200)
	Opt.	1	392(864)	427(942)	460(1014)	544(1200)
	Opt.	2	356(784)	389(858)	420(925)	499(1100)
	Opt.	3	319(703)	350(772)	379(835)	454(1000)
4 Pass.	Prob.	1,2,3	722(1591)	776(1710)	825(1818)	952(2100)
	Opt.	1	722(1591)	776(1710)	825(1818)	952(2100)
	Opt.	2	685(1510)	738(1624)	784(1729)	907(2000)
	Opt.	3	648(1430)	698(1539)	744(1640)	862(1900)
5 Pass.	Prob.	1,2,3	869(1916)	931(2053)	987(2177)	1134(2500)
	Opt.	1	869(1916)	931(2053)	987(2177)	1134(2500)
	Opt.	2	832(1835)	892(1967)	947(2087)	1089(2400)
	Opt.	3	796(1754)	853(1881)	906(1998)	1043(2300)
Multi-purpose	Prob.	1,2,3	1424(3139)	1515(3339)	1598(3522)	1814(4000)
	Opt.	1	1424(3139)	1515(3339)	1598(3522)	1814(4000)
	Opt.	2	1349(2975)	1437(3167)	1516(3342)	1724(3800)
	Opt.	3	1239(2731)	1320(2911)	1394(3074)	1588(3500

[a] 1 = 1980-1985, 2 = 1985-1990, 3 = 1990-2000.

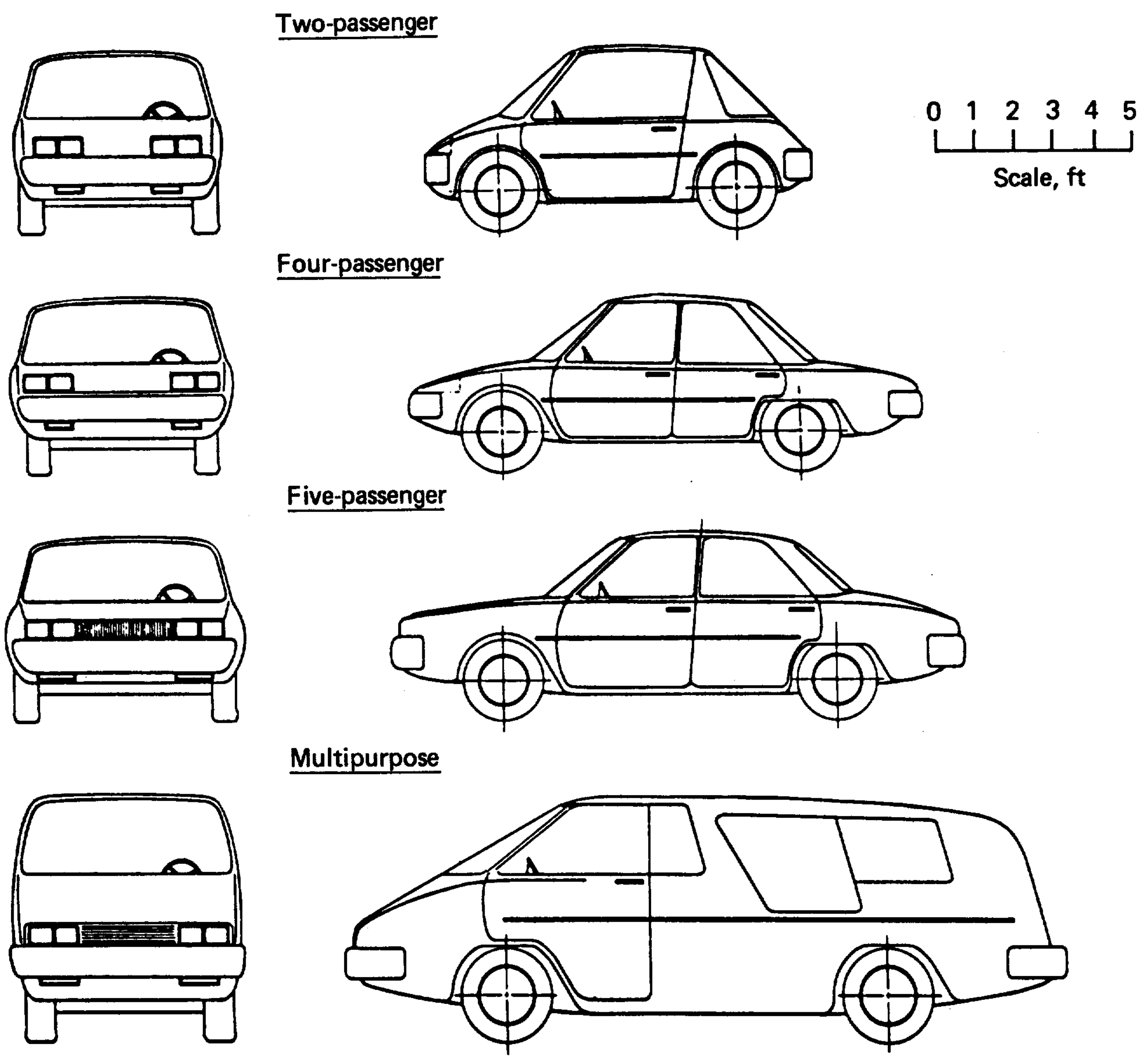


FIG. 1. Representative vehicle sizes.

TABLE 8. Payloads and frontal areas of representative vehicles.

Vehicle type	Maximum payload kg	(lb)	Frontal area m^2	(ft^2)
Two-passenger	181	(400)	1.67	(18)
Four-passenger	318	(700)	1.86	(20)
Five-passenger	408	(900)	2.14	(23)
Multipurpose	907	(2000)	2.79	(30)

The next three levels of performance can be considered as suitable for vehicles designed for specific tasks. These could include commuter automobiles or delivery vans.

Limited-performance vehicles have a range of 120 km and a power-to-mass ratio of 0.026 kW/kg (0.016 hp/lb). This power-to-mass ratio is the minimum necessary to meet the acceleration requirement of the J227a(D) driving cycle, which is representative of urban driving.* Overnight refueling or recharging is permitted.

Intermediate-performance vehicles have range and acceleration capabilities lying between those of the limited-performance and ICE-equivalent vehicles. Range is 240 km and the power-to-mass ratio is 0.033 kW/kg (0.02 hp/lb). They represent the lower end of the future ICE-performance spectrum.

Minimum-performance vehicles to simulate the characteristics of the very low performance requirements of urban commercial driving were required to have a power-to-mass ratio of 0.01 kW/kg (0.006 hp/lb) and an 80-km range over the less-demanding SAEa(C) driving cycle.

The four performance levels specified are summarized in Table 9. We did not attempt to predict what performance is needed for consumer acceptance, but wished to determine the sensitivity of energy-storage devices and propulsion systems to vehicle-performance level. In general each performance level is

* The Federal Urban Driving Cycle requires a power-to-mass ratio of only 0.02 kW/kg (0.012 hp/lb).

TABLE 9. Performance-level requirements.

Performance level	Range[a] km	Range[a] (mi)	Power-to-mass ratio[b] kW/kg	Power-to-mass ratio[b] (hp/lb)	Approximate full-power acceleration time (s) 0-48 km/h (0-30 mph)	Approximate full-power acceleration time (s) 0-97 km/h (0-60 mph)
General-purpose vehicles						
Equivalent	400	(250)[c]	0.049	(0.03)	4.7	14.8
Intermediate	240	(150)	0.033	(0.02)	6.8	20.4
Specific-mission vehicles						
Limited	120	(75)	0.026	(0.016)	8.4	24.3
Minimum	80	(50)	0.016	(0.01)	13.2	35.1

[a] Range determined at 80% fuel usage or 80% storage device discharge.

[b] Power measured at input to transmission, mass is curb mass plus a test mass of 136 kg (300 lb).

[c] Includes rapid (5-15 min) refueling or recharging requirement.

defined by both range and acceleration capability. In some cases we also examined the results of considering short range with high power levels and long range with low power levels. Range is determined by the point at which the energy-storage device is 80% discharged or, in the case of a fueled vehicle, the point when 80% of the fuel is consumed. Acceleration performance is characterized by the peak power-to-vehicle mass ratio. There is a direct statistical relationship between this ratio and vehicle-acceleration capability and performance. Peak power is measured at the input to the transmission, and the vehicle mass is calculated as the vehicle curb mass plus 136 kg (300 lb).

Characterization of Vehicles

Having defined four representative vehicle sizes and four standard performance levels, we evaluated and compared ICE and energy-storage propulsion systems in 16 vehicles having combinations of size and performance levels. To establish a baseline for comparison we conceptually designed an ICE automobile for each of the size and performance categories and characterized each in terms of the following:

- Curb mass
- Engine horsepower
- Mass of engine and engine accessories
- Transmission mass
- Engine-compartment volume
- Overall vehicle length

The results of this characterization are given in Volume 2 of the 1978 Study.

We then conceptually replaced the ICE propulsion system of each vehicle with various energy-storage propulsion systems and calculated the resulting vehicle mass, size, energy use, and cost for each performance level.

ENERGY-STORAGE PROPULSION SYSTEMS

Using the criteria and procedures that were established, the following energy-storage devices were selected for analysis.

- Secondary batteries
  - Lead/acid
  - Nickel/iron
  - Nickel/zinc
  - Lithium/iron sulfide
  - Sodium/sulfur (cer)
  - Sodium/sulfur (glass)
  - Zinc/chlorine
- Mechanical storage
  - Compressed-air storage (using waste heat)
  - Hydraulic accumulator
  - Flywheel (isotropic and fiber composite)
- Hydrogen storage
  - Liquid hydrogen
  - Magnesium/nickel hydride
  - Iron/titanium hydride
  - Glass microspheres
- Thermal storage
  - Lithium/fluoride

The Automotive End-Use Panel and the Energy-Storage Panels selected seven generic types of energy-storage propulsion systems to be analyzed:

- All-battery systems
- Battery/flywheel systems
- Dual-fueled hybrid systems
- Power-leveling hybrid systems
- Hydrogen-fueled ICE systems
- Hydrogen fuel-cell systems
- Thermal-storage/ICE systems

Mechanical storage devices were judged unsuitable as primary sources of propulsion and were limited to power-leveling functions. Battery/flywheel EVs were included to evaluate the effect of power leveling, which can reduce the peak-power requirements for all-battery vehicles. The dual-fueled hybrid system is a minimum or limited-range battery/flywheel system to which a small ICE is coupled for hybrid operation when vehicle range extension is required. The power-leveling hybrid systems permit analysis of the effect of mechanical storage devices and batteries employed to level ICE engine-power requirements. Two additional systems were examined to see if turbines are better than the ICE for this application. These systems combine a turbine with a small power-boosting flywheel.

The Automotive End-Use Panel also considered roadway-powered electric vehicles, which would use power sources built into the roadway while traveling on arterial routes, and on-board batteries for less-demanding off-arterial service. Given successful technical development and an inventory of powered roadways, such a system could provide unlimited range for specially equipped electric or hybrid vehicles.

All-Battery Systems

The generalized all-battery electric propulsion system is shown in Fig. 2. The major electrical components are the propulsion batteries, a battery controller containing a dc single-phase, pulse-width-modulated chopper, and a dc separately excited traction motor. The traction motor supplies power to the wheels through a transmission designed to match road load to motor output. Transmission characteristics are those of a three-speed automatic having torque-converter lock up. The diagram also shows battery and vehicle accessories. In the analysis, battery accessories were accounted for in determining the specific energy, specific power, and cost of the battery system. Vehicle accessories (accessory battery, lights, etc.) were assumed to be the same for

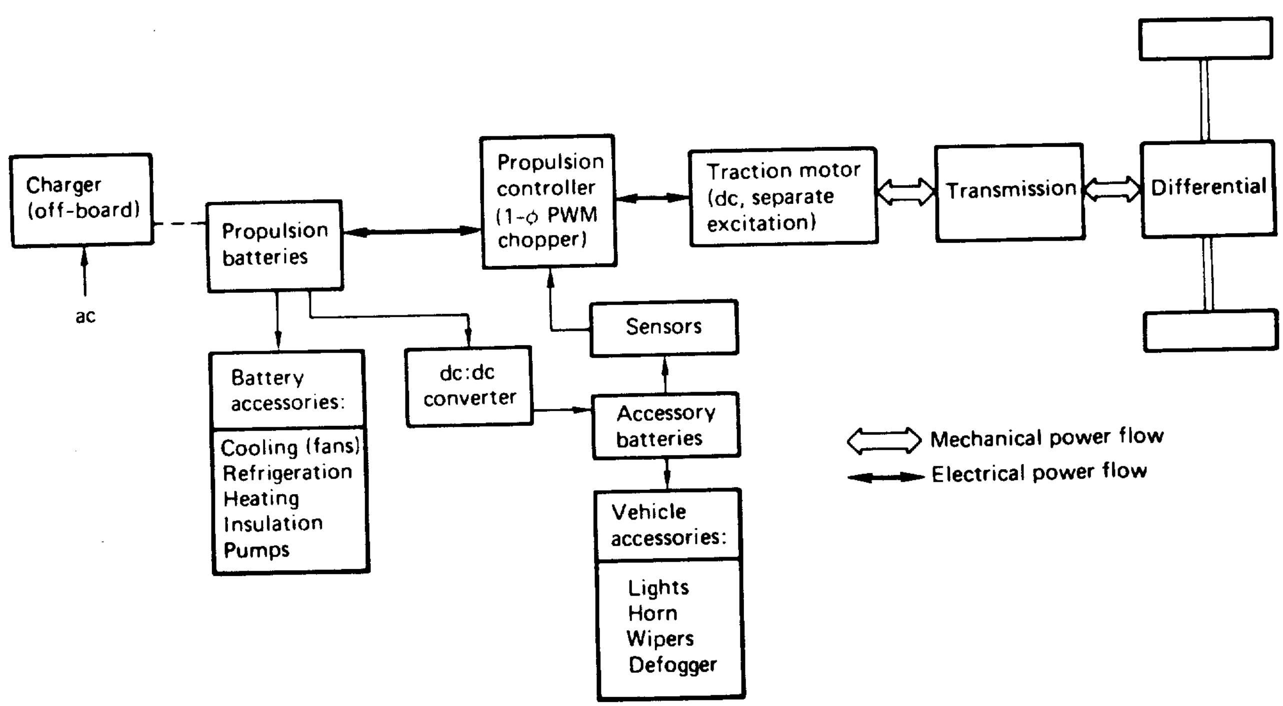


FIG. 2. Block diagram of an all-battery propulsion system.

all vehicles, and their effect on performance was not considered in the analysis. No vehicle heating or cooling was considered in any of the analyses for the same reason.

Battery/Flywheel Systems

A simplified block diagram of the battery/flywheel system is shown in Fig. 3. The major electrical components (battery, controller, and traction motor) and the battery and vehicle accessories are the same as shown in Fig. 2. For the battery/flywheel vehicle, a gearbox and speed reducer link the flywheel to the driveshaft between the traction motor and transmission. A continuously variable transmission (CVT) links the driveshaft to the road load and compensates for flywheel run-down. The system controller optimizes system operation.

In sizing the components of battery/flywheel EVs we specified a battery having sufficient power to propel the vehicle at 80 km/h (55 mph) over a level road, with 10% additional power to charge the flywheel while the vehicle is traveling at 80 km/h. The batteries are sized to contain sufficient energy to propel the vehicle its specified range. The flywheel is sized to meet the specified vehicle power-to-mass ratio with the batteries at full power and to have sufficient energy to propel the vehicle for 0.8 km (0.5 mi) up a 6% grade with the batteries at full power.

Dual-Fueled Hybrids

The dual-fueled hybrid propulsion system is shown in Fig. 4. This vehicle operates as a battery/flywheel electric vehicle for most operations and also contains a small ICE to provide hybrid propulsion for range extension when required. The flywheel and battery are sized in accordance with the principles established for battery/flywheel EVs, but for ranges of 80 and 120 km as an electric. The range-extending heat engine is sized to propel a vehicle up a 3% grade at 72 km/h (45 mph). With the flywheel the dual-fueled hybrid power system can provide ICE-equivalent performance.

Power-Leveling Hybrid Systems

We evaluated six power-leveling classes:

- ICE/flywheel
- ICE/hydraulic accumulator

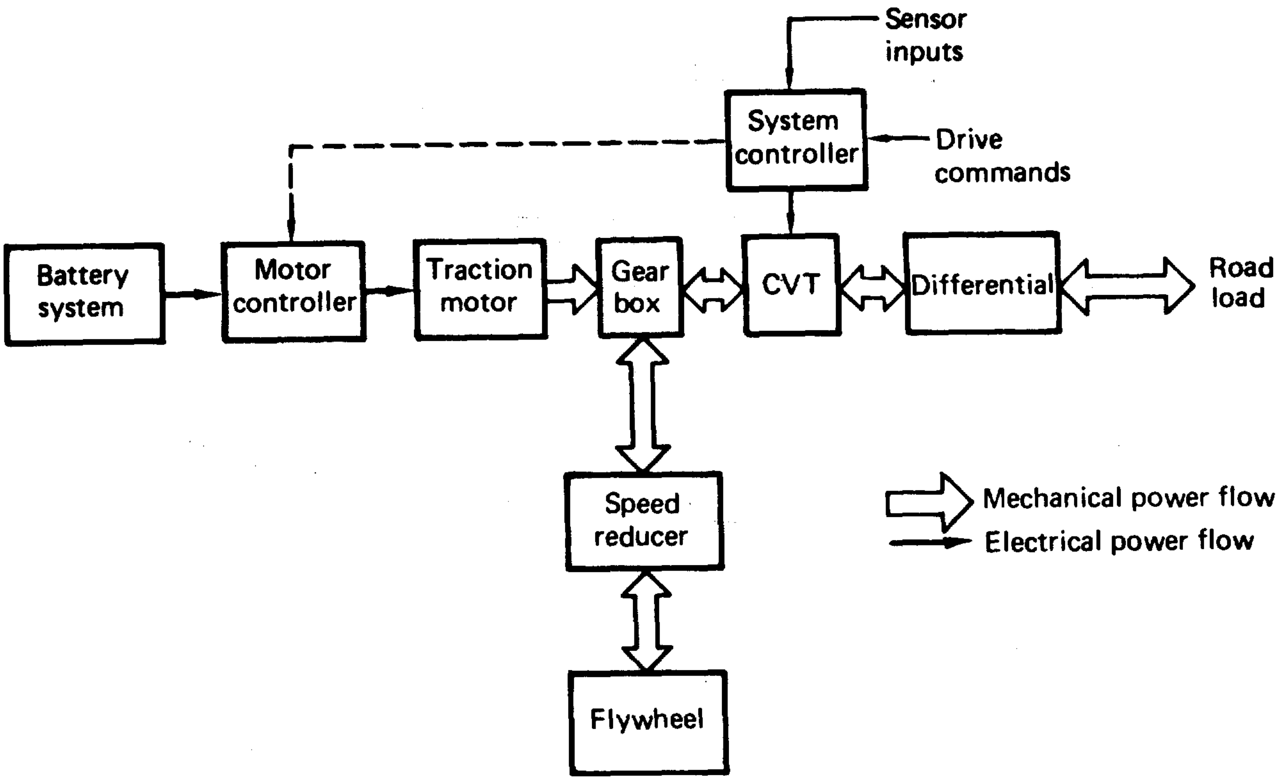


FIG. 3. Simplified block diagram of battery/flywheel propulsion system.

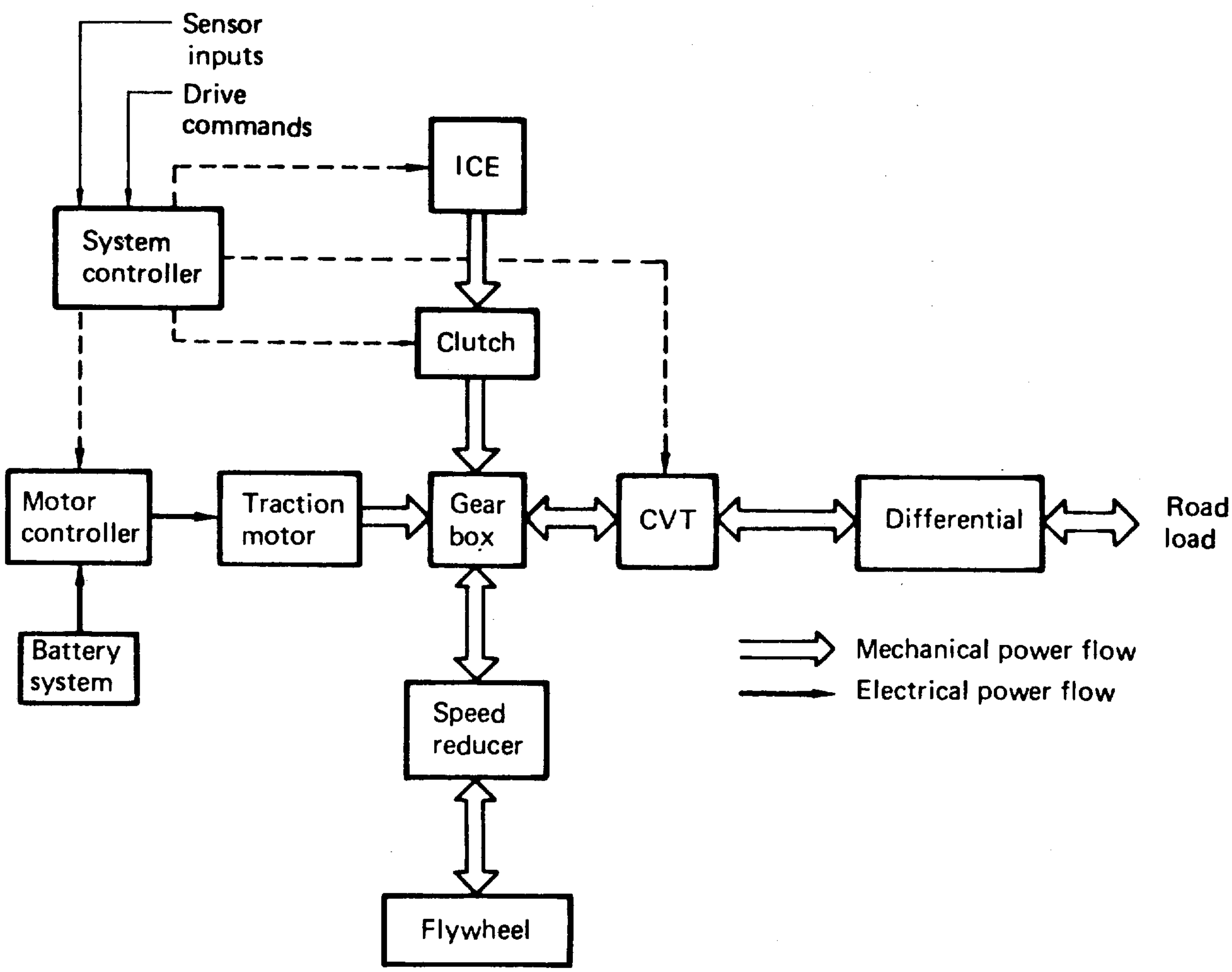


FIG. 4. Simplified block diagram of the dual-fueled hybrid drive power system.

- ICE/compressed-air storage
- ICE/battery hybrid
- Turbine/isotropic flywheel
- Turbine/fiber-composite flywheel

The power-transmission systems of these vehicles allow either a combustion engine (CE) or a storage device, or both, to be used for propulsion power.

The storage device allows the engine to run with nearly constant output power in a region of low-fuel consumption and controlled emission. It satisfies the changing power requirements of the vehicle by adding to or receiving power from the ICE. It also provides a means of recovering kinetic energy during vehicle deceleration (regenerative braking). We did not consider the dual-fueled hybrid as a power-leveling hybrid because it is operated as a battery/flywheel electric vehicle most of the time.

There is considerable design flexibility in sizing components for power-leveling hybrids, so we specified two types. The engine of the Type 1 power-leveling hybrid is just large enough to power the vehicle at 80 km/h on a level road with 10% power held in reserve for charging the storage device. The storage device is sized to provide additional energy above maximum engine output to enable the vehicle to travel 3.2 km (2 mi) up a 6% grade at 88 km/h. Thus, this hybrid has maximum energy storage with a heat engine just large enough for extended-range operation.

The engine of the Type 2 CE hybrid is sized to power the vehicle up a 3% grade at 88 km/h (55 mph). The storage device is sized to provide enough energy, in combination with the maximum CE output, to enable the vehicle to travel 0.8 km (0.5 mi) up a 6% grade at 88 km/h (55 mph). The Type 2 hybrid lies near the minimum-storage maximum-CE end of the spectrum.

Each of the hybrid systems listed above was evaluated in both the Type 1 and Type 2 configurations.

Each of the six power-leveling propulsion systems is different, both in the components they use and in their detailed operation. However, all the systems examined in this study can be simplified mathematically by means of a single-node power-flow diagram. Figure 5 shows the simplified single-node model used for the analysis of the ICE/compressed-air hybrid. Detailed descriptions of the ICE/hybrids are given in Volume 2. The prospects for the turbine engine are discussed there also. The design and operating procedure for these hybrid systems are the same as for the ICE/energy-storage hybrid with

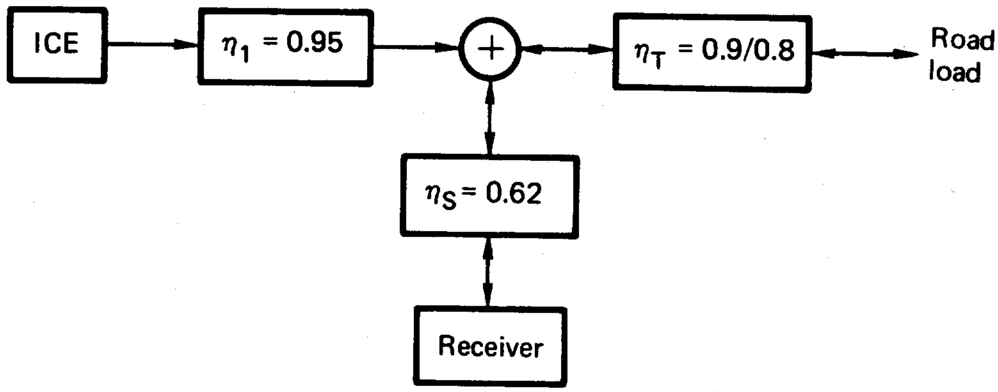


FIG. 5. Power flow/efficiency diagram for the ICE/compressed-air vehicle. Efficiencies are shown as peak/average. When only one number is given, it is a composite of peak and average efficiencies. Composite efficiency is derived from 0.57 average charging efficiency and 0.68 average discharging efficiency.

the substitution of the turbine for the ICE. A simplified block diagram of an ICE system is shown in Fig. 6. Table 10 presents the projected performance levels for the automotive gas turbines that were used in the analysis.

In evaluating flywheel hybrids both the isotropic and composite flywheels were used in these systems and the average energy loss per drive cycle (2 min) is given as a fraction of the total flywheel energy at the required probability levels and for the applicable time periods (see Table 11).

We also evaluated an ICE/battery-hybrid system. For the battery we used a high-specific-power nickel/zinc device, thus providing a comparison of this simpler mechanical system with the high-powered ICE/flywheel systems. For this case, the ICE was sized to provide 10% more power than required to propel the vehicle at 88 km/h (55 mph) along a level road, allowing battery recharge during cruise. The battery was required to have enough power to provide the vehicle with a peak-power-to-mass ratio of 0.049 kW/kg. The battery also had to have enough energy so the vehicle could travel 0.8 km (0.5 mi) up a 6% grade at 88 km/hr (55 mph). This is the same energy requirement as the Type 2 hybrid.

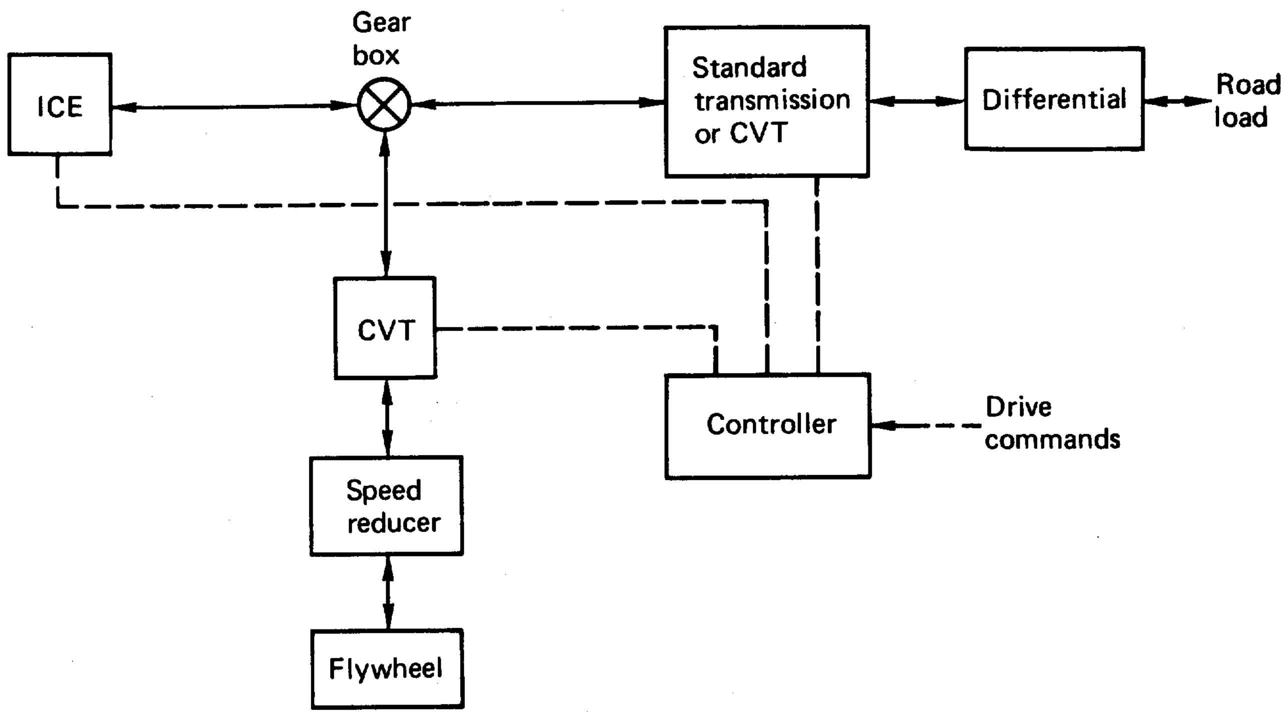


FIG. 6. Typical power-leveling-hybrid functional block diagram.

TABLE 10. Projected performance levels of automotive gas-turbine engines.

Time period	Prob. level	Mass/power ratio, kg/kW	(lb/hp)	Specific fuel consumption kg/kWh	(lb/hph)	Fuel economy km/	(mpg)
Present	—	3.4	(5.5)	0.45	(0.75)	8.1	(19)
1980-1985	Prob.	2.7	(4.5)	0.37	(0.60)	9.8	(23)
1985-1990	Prob.	2.4	(4.0)	0.29	(0.48)	12.7	(30)
1990-2000	Prob.	2.2	(3.6)	0.22	(0.36)	16.1	(38)
Present	—	—	—	—	—	—	—
1980-1985	Opt.	2.3	(3.8)	0.33	(0.54)	11.5	(27)
1985-1990	Opt.	1.8	(3.0)	0.27	(0.44)	14.4	(34)
1990-2000	Opt.	1.3	(2.2)	0.19	(0.32)	19.5	(46)

TABLE 11. Flywheel energy loss on a fraction of total flywheel-energy-storage capacity.

Prob. level %	1980-1985	1985-1990	1990-2000
Probable	0.04	0.03	0.02
Optimistic	0.02	0.01	0.004

Chemical Systems

Hydrogen-storage systems considered in this study are:

- Liquid-hydrogen systems
- Iron/titanium hydride
- Magnesium/nickel hydride
- Dual hydride
- Microsphere hydrogen-storage systems

All of these systems are similar to the basic ICE propulsion systems except for the fuel-storage system and the characteristics of the hydrogen-fueled engine. Figure 7 shows the fuel-storage system for liquid hydrogen and Fig. 8 shows the fuel-storage system for the dual hydride comprised of TiFe and Mg-based beds. In addition, an EV propulsion system was analyzed using an FeTi hydrogen-storage system coupled with a fuel cell for steady-state power and a NiZn booster battery for peak power requirements. The configuration of this system is shown in Fig. 9.

Thermal-Storage Systems

A thermal-storage propulsion system uses a storage device capable of transporting or transferring heat out of the unit to a heat engine. The storage device contains a material that can store a usable amount of heat at a high temperature. The major assumptions and projections used in the analysis of thermal-storage systems are given in Table 12. The propulsion system

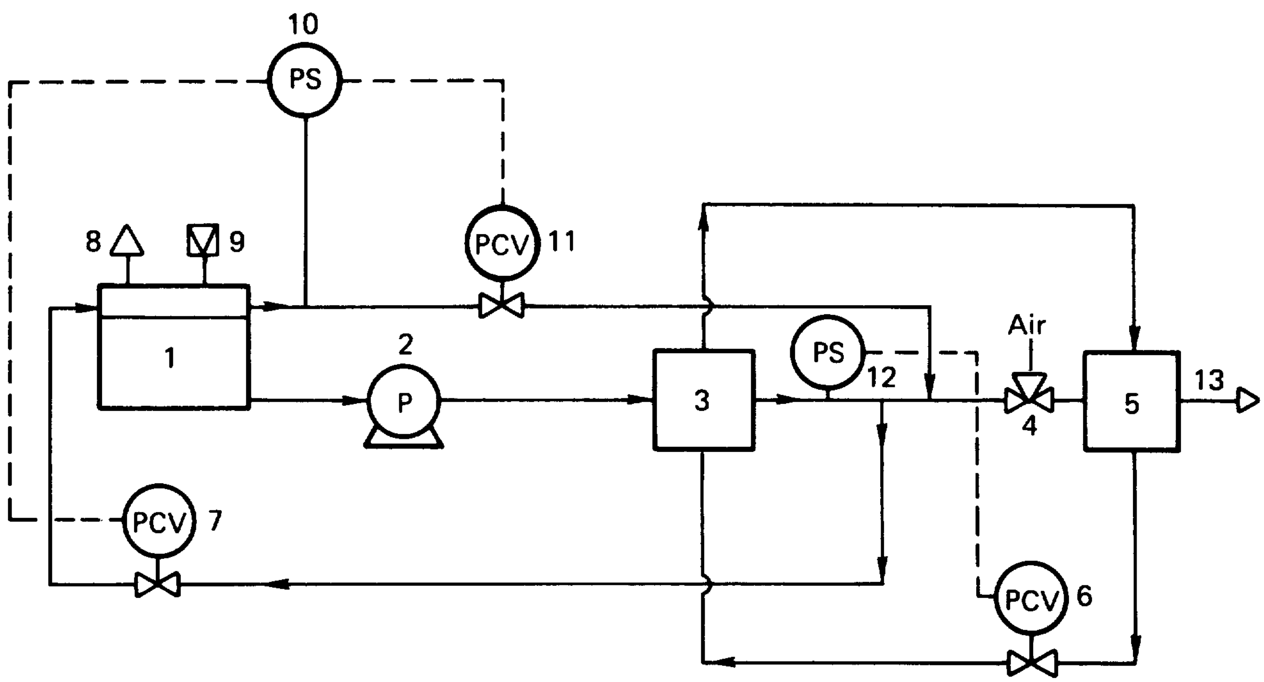


FIG. 7. Liquid-hydrogen system. Major elements include: (1) liquid-hydrogen tank; (2) liquid-hydrogen pump; (3) liquid-hydrogen vaporizer; (4) accelerator-controlled hydrogen admission valve; (5) engine; (6) engine-coolant circulation valve (pressure controlled); (7) tank pressurizing valve (pressure controlled); (8) tank vent; (9) quick-connect fill; (10) pressure sensor; (11) pressure-controlled valve; (12) pressure sensor; (13) exhaust-gas outlet.

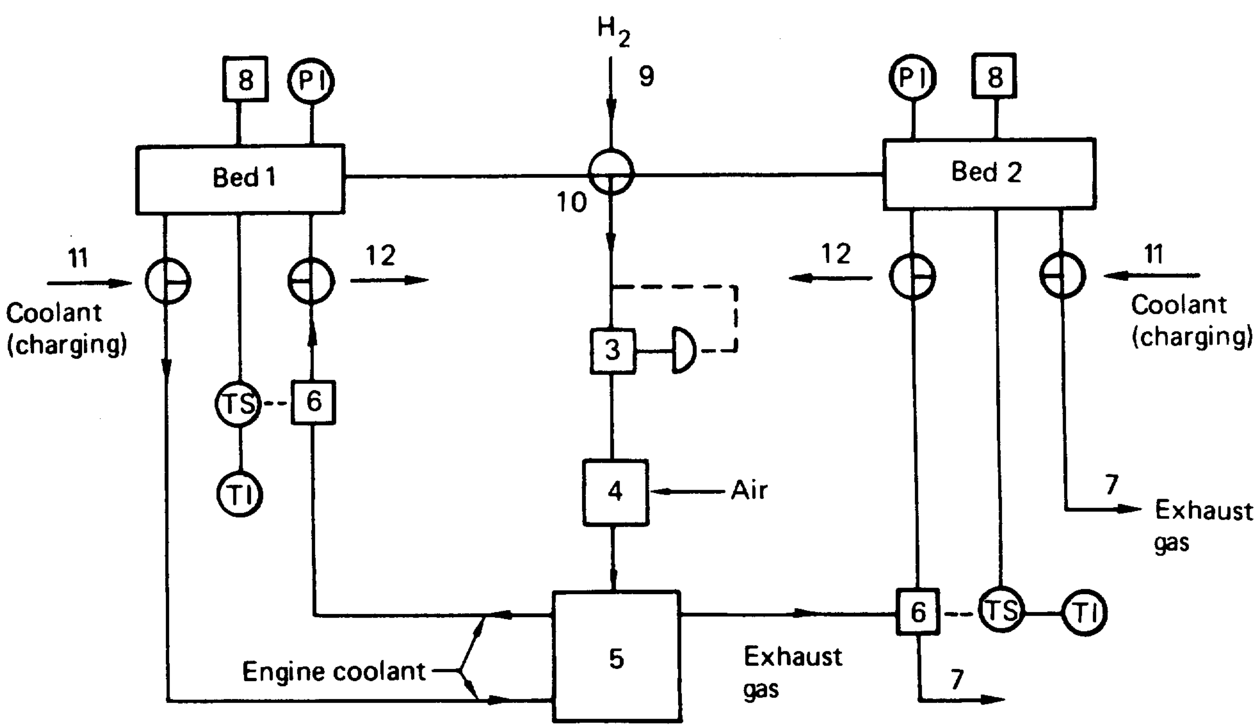


FIG. 8. Simplified diagram of a power-conversion system for a dual-hydride system. Major components include: The TiFe-based hydride in Bed 1, the Mg-based hydride (MgH_2 catalyzed with 10 wt% Ni) in Bed 2, pressure regulator (3), gas carburetor (4), engine (5), relief valves (8), and liquid-coolant circulation (11,12).

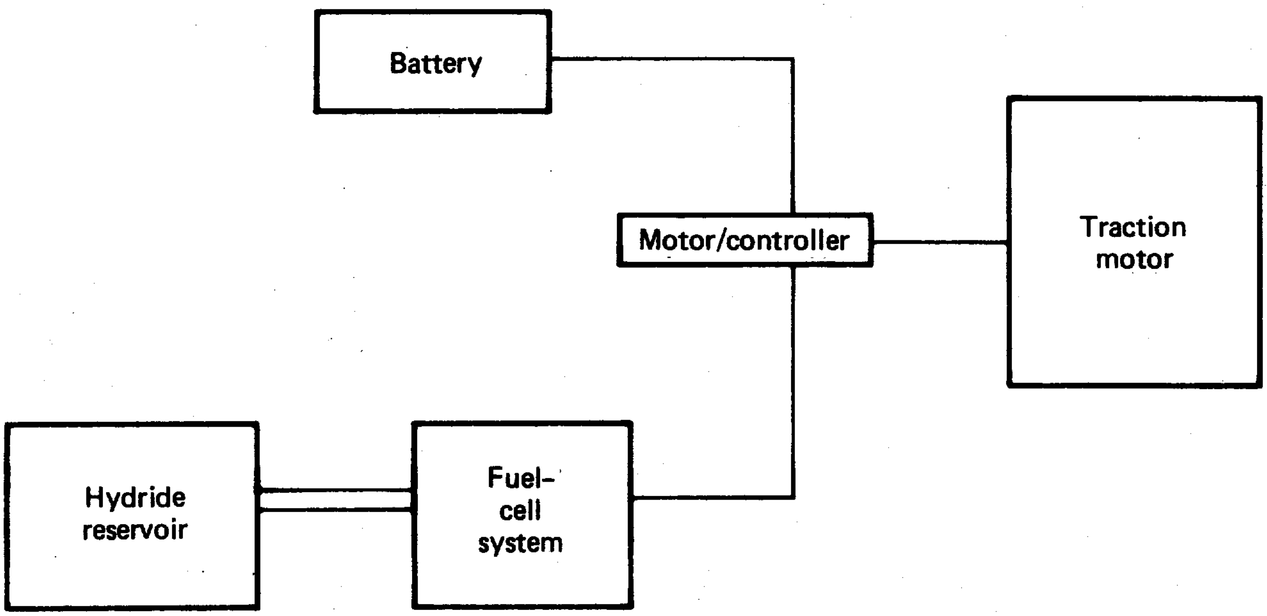


FIG. 9. Block diagram of the power train for a fuel cell/battery vehicle.

consists of a vacuum-insulated, LiF fused-salt storage material in a stainless-steel container that drives a Stirling engine via a two-phase potassium heat transport mechanism. Refueling cost is based on electric recharging. Figure 10 shows a block diagram of the system analyzed.

Characterization of Propulsion Systems

For each generic energy-storage propulsion system (ESPS), the mass, volume, cost characteristics, and operational parameters (efficiency, peak-power capacity, etc.) of all the components used had to be determined. The first step was to conceptually design the ESPS to be analyzed. The next step was to define as completely as possible the characteristics and operational parameters of each propulsion-system component. The characteristics of nonstorage propulsion components were either statistically derived using current component data or estimated by the Energy Storage Panels and the Automotive End-Use Panel if they were nonproduction items. The masses, volumes, and costs of the

TABLE 12. Highly optimistic thermal-storage analysis assumptions.

Storage projections[a]	
Energy density (gravimetric), Wh/kg	244
Energy density (volumetric), Wh/liter	263
Short duration (15-30 s) peak power, W/kg	460
Maximum continuous peak power, W/kg	192
Average power loss, W/kg	1.42
Lifetime, y	10
Engine assumptions	
Average efficiency, %	40
Engine mass (lb) = 4.4(hp) + 40	
Cost projections	
Storage system (1990-2000), $/kg	4.80
Residual value, $/kg	1.20
Refueling cost (electric), $/kWh	0.03
Engine cost ($) = 3.8(hp) + 196	

[a] Projections are for total system without engine.

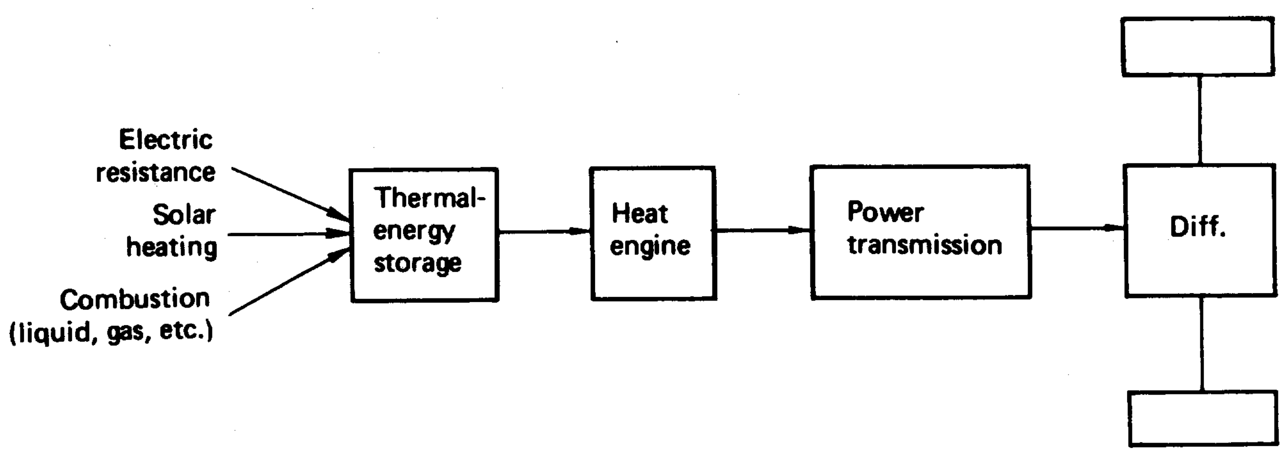


FIG. 10. High-temperature thermal-energy storage (highway vehicle application).

components used (excluding those of the storage device and its accessories) were obtained by the Automotive End-Use Panel for each propulsion system evaluated. The Energy Storage Panels developed the corresponding data on the storage devices. Some propulsion components such as transmissions were common to many of the ESPS and ICE baseline vehicles. For these and other propulsion elements common characteristics were used in the analysis.

The analysis procedure requires the simulated evaluation of the ESPS vehicle over a standard driving cycle. This is necessary to determine if the performance parameters meet the specifications. This procedure necessitates that each power-train component's performance be characterized under vehicle operating conditions. For example, transmission characterization takes the form of a graph of efficiency vs speed. Electric-motor/controller combinations are characterized by curves of efficiency vs speed for different motor loads. For heat engines the analysis uses an engine-performance map that plots fuel-consumption contours vs engine hp and engine speed coordinates. For conventional ICE systems, performance maps are obtained by laboratory measurements. For nonconventional engines, hypothetical performance maps had to be constructed. Figure 11 is a computer-generated performance map for a 60-hp hydrogen-fueled ICE. The map was generated by a computer routine based on engine-cycle analysis and hydrogen properties, and it is representative of the H_2 engines used in our evaluation of hydrogen-fueled systems.

Storage-Device and Propulsion System Combinations

The number of possible combinations of storage devices, time periods, performance levels, vehicle types, and likelihood levels is enormous. The number selected for this study was made manageable by limiting the presentations in many cases to five-passenger vehicles. Our analyses showed that mass and cost comparisons based on the five-passenger vehicles were representative of similar comparisons with other vehicle sizes. The number was further reduced by noting that some performance levels were impractical. Thus battery/flywheel EVs having less than equivalent acceleration would be anomalous as would dual-fueled hybrids having less than equivalent acceleration and range. A complete matrix of energy-storage vehicles considered in the study is shown in Table 13.

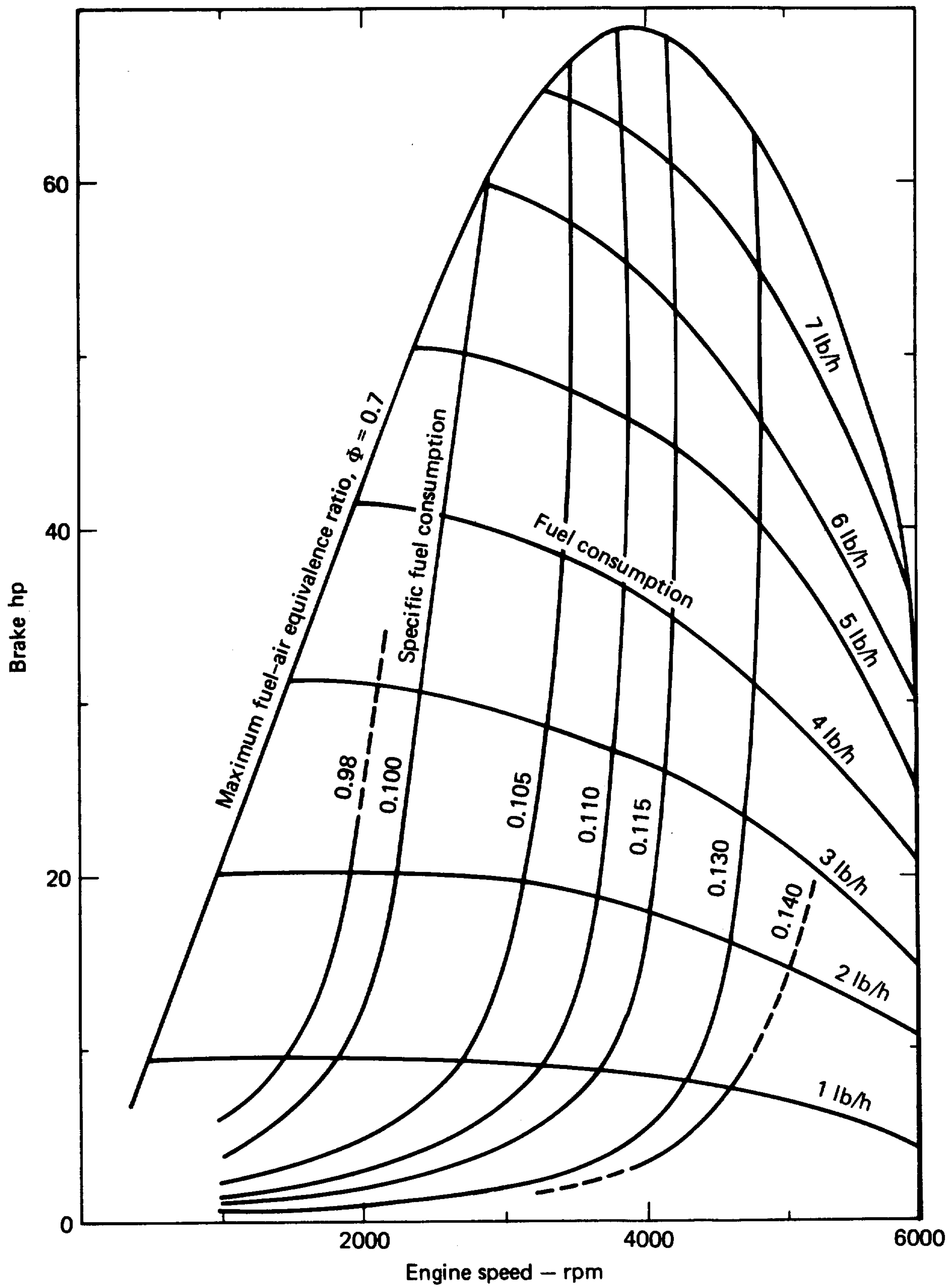


FIG. 11. Performance map for an air-aspirated hydrogen-fueled ICE. Piston displacement = 135.4 in.^{3}; compression ratio = 10:1; rated power = 60 hp at 2462 rpm.

TABLE 13. Matrix of propulsion systems evaluated for performance and cost.

	Time period			Performance levels[a]				Vehicle[b] types	Prob. level	No. of vehicles
	1980-1985	1985-1990	1990-2000	Min.	Lim.	Int.	Equiv.			
All-battery system										
Pb/acid	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Ni/Fe	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Ni/Zn	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
$LiAl/FeS_2$		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	66
Zn/Cl_2	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Na/S(cer)		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	64
Na/S(glass)		x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	64
H_2 Storage systems										
$FeTiH_x$/fuel cell	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
Microspheres/ ICE		x		x	x	x	x	2P, 4P 5P,MPV	Opt.	16
Dual hydride/ ICE	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Prob.& Opt.	96
FeTi hydride/ ICE	x	x	x	x	x	x	x	2P, 4P 5P,MPV	Opt.	96
Liquid H_2		x	x	x	x	x		2P, 4P 5P,MPV	Prob.	9
Battery/flywheel electric systems										
Pb/acid	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
Ni/Fe	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
Ni/Zn	x	x	x	x	x	x	x	5P	Prob.& Opt.	24
$LiAl/FeS_2$		x	x	x	x	x	x	5P	Prob.& Opt.	16
Zn/Cl_2	x	x	x	x	x	x	x	5P	Prob.& Opt.	24

TABLE 13.(Cont.)

	Time period			Performance levels[a]				Vehicle[b] types	Prob. level	No. of vehicles
	1980-1985	1985-1990	1990-2000	Min.	Lim.	Int.	Equiv.			
Na/S(cer)		x	x	x	x	x	x	5P	Prob.& Opt.	16
Na/S(glass)		x	x	x	x	x	x	5P	Prob.& Opt.	16
				Dual-fueled hybrids						
Pb/acid/ fly/ICE	x	x	x				x	5P	Prob.& Opt.	6
NiFe/ fly/ICE	x	x	x				x	5P	Prob.& Opt.	6
NiZn/ fly/ICE	x	x	x				x	5P	Prob.& Opt.	6
$LiAl/FeS_2$/ fly/ICE		x	x				x	5P	Prob.& Opt.	4
$ZnCL_2$/ fly/ICE	x	x	x				x	5P	Prob.& Opt.	6
NaS(cer)/ fly/ICE		x	x				x	5P	Prob.& Opt.	4
NaS(Glass)/ fly/ICE		x	x				x	5P	Prob.& Opt.	4
				Power-leveling hybrids						
Compressed air	x	x	x	Type 1 and Type 2				5P	Prob.	6
Hydraulic accumulator	x	x	x	Type 1 and Type 2				5P	Prob.	6
Composite isotropic rotor flywheel	x	x	x	Type 1 and Type 2				5P	Prob.	6
Battery	x	x	x	Type 1 and Type 2				5P	Prob.	6

a Performance level refers primarily to vehicle power/mass ratio. Vehicle masses are determined as a function of range to include all combinations of power and range.

b The abbreviations 2P, 4P, 5P and MPV stand for two-passenger, four-passenger, five-passenger, and multipurpose vehicle, respectively.

EVALUATION PROCESS

To evaluate the energy-storage devices, we held vehicle function and performance constant and treated other vehicle parameters as variables. We began by assuming sets of vehicle performance and functional requirements, including range, acceleration, passenger volume, and payload. In this context, range and acceleration were in most cases combined to define the four specific performance levels. However, late in the study, a few cases were analyzed where vehicles of fixed-acceleration capability were characterized as a function of variable range. These vehicle requirements along with the storage-device characteristics supplied by the Energy Storage Panels comprised the input to our analysis models, which in turn enabled us to design ESVs described by mass, energy use, cost, and component parameters.

Obviously we could have used other methods. For example, we could have held vehicle mass and the storage-device mass fraction constant, using performance as the model outcome. However, we felt that performance and cost were the critical issues determining market acceptance. We therefore selected performance as one of the independent variables. Cost, which is difficult to treat as an independent variable, became a model output and one of the principal considerations.

The end-use analysis consisted of five steps:

1. We defined four performance levels in terms of range and acceleration capability. These were designated, from the least demanding to the most demanding, as the minimum, limited, intermediate, and ICE-equivalent levels.

2. We defined four representative vehicles in terms of passenger volume, payload, and frontal area. These are the two-, four-, and five-passenger vehicles and the multipurpose vehicle (MPV).

3. We then specified the physical characteristics of each of the four vehicles for each of the four performance levels, assuming an ICE power system. The vehicles thus specified became the baseline vehicles used as a starting point for our modeling procedure. The characteristics specified included, among others, vehicle curb mass, engine power, engine-system mass, vehicle length, and engine-compartment volume.

4. We selected the automobile propulsion systems that incorporated the various energy-storage devices and specified each of the propulsion components

in terms of their physical and propulsion characteristics (i.e., mass, volume, and efficiency).

5. We used computer models to remove the ICE propulsion systems of the baseline vehicles and replace them with the various energy-storage propulsion systems to provide the same performance as the baseline vehicle. The outputs of the model are the mass, size, energy use, and cost of the resultant ESV. These outputs provide a measure of the suitability of the different energy-storage propulsion systems for particular vehicles at particular performance levels.

Mass and Volume Analysis

In our analysis we replaced the ICE propulsion systems of the baseline vehicles with energy-storage propulsion systems having, in general, different masses and volumes from those of the baseline systems.

Given optimal vehicle design, the overall change in vehicle mass is greater than the difference in propulsion-system masses. This is because the structural members, suspension system, wheels, tires, and body structure supporting the new propulsion system will also be affected by component mass changes. Historically, an empirically derived mass propagation factor (MPF) has been used to calculate increases or decreases in overall vehicle mass stemming from changes in propulsion systems. That is, a new power system weighing x amount more than the previous unit would increase the vehicle mass by $(1 + MPF)x$.

In our analysis we assessed separately the impacts of changes in propulsion system mass and that of volume. For mass changes we used an MPF of 0.3 except for the optimistic cases in the 1985-1990 time period, where we used an MPF of 0.2, and the 1990-2000 time period where we used an MPF of 0.1. For volume changes we first assessed changes in vehicle length caused by changes in propulsion-system volume. Then we determined the change in vehicle mass caused by the length variation, assuming a constant body mass per unit length.

The methodology implicity assumes that the volume and mass of the baseline ICE vehicle associated with passengers and payload remains unchanged during the transformation of the ICE vehicle to energy-storage vehicle. This assumption also applies to nonpropulsion accessories such as lights, windshield wipers, ventilation equipment, etc.

Vehicle Energy and Power Calculations

The calculations used to determine the energy and power needs of a vehicle consist of solving a set of power and energy equations characterizing the simulated motion of the vehicle over a standard driving cycle. The equations are based on a set of generalized expressions describing the tractive resistance forces acting on a vehicle. We used three force equations to define the air-drag force (f_D), the rolling-resistance force (f_R), and the force on grade (f_G); f_D is a function of vehicle air-drag coefficient, vehicle frontal area, and vehicle velocity; f_R is a function of vehicle mass and velocity; and f_G depends on vehicle mass and road grade.

Since acceleration is equal to force divided by mass, and power may be expressed as force times velocity, the vehicle power required (at the output of the drive train) is given by:

$$P = mav - vf_T \,, \qquad (1)$$

where

m = mass,
a = acceleration,
v = velocity, and
f_T = $f_C + f_R + f_G$.

Energy may be calculated as the integral of force and distance or power and time:

$$\epsilon = \int f ds = \int P dt. \qquad (2)$$

Since the air-drag coefficient and frontal area of baseline vehicles are specified and assumed unchanging, vehicle mass and the driving-cycle velocity profile are sufficient to determine the vehicle roadload power and energy needs. These in turn define power and energy requirements for the energy-storage device if the drivetrain-component efficiencies are known.

A flow diagram of the model used for calculating energy and power needs of all-battery electric vehicles is shown in Fig. 12 (a similar procedure is used for other ESPS calculations). Once a particular battery, driving cycle, and drive train have been elected, the model steps through the driving-cycle

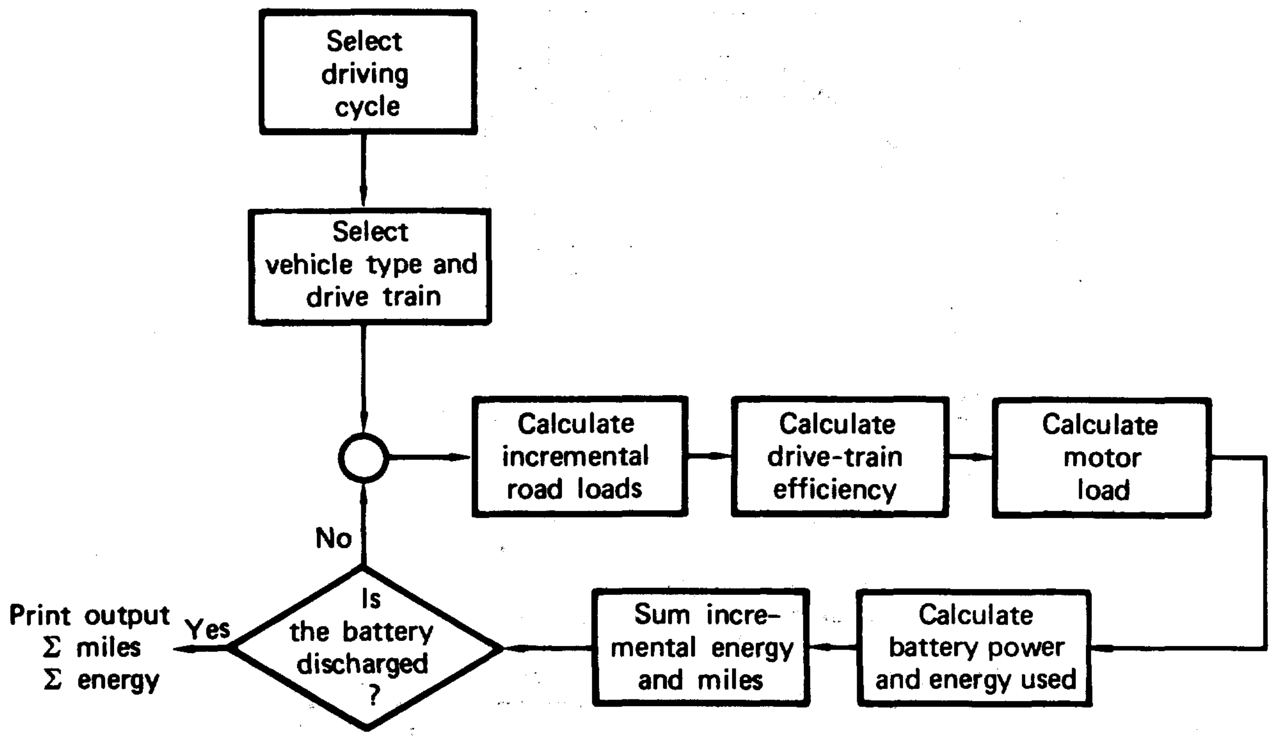
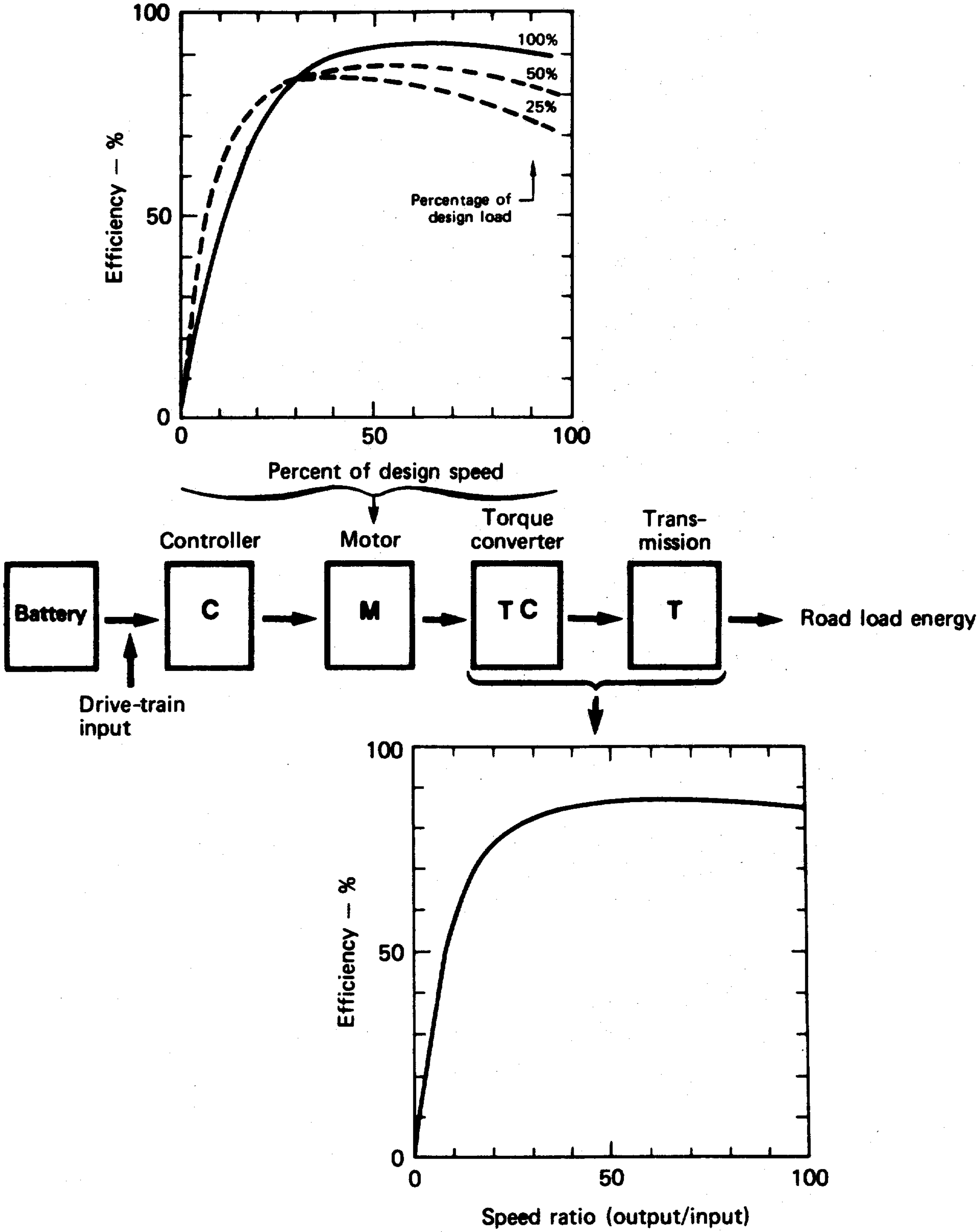


FIG. 12. Flow diagram of LLL vehicle model.

velocity profile in 1-s time periods and calculates road loads, efficiencies, and other vehicle parameters for each time increment. Both summations and instantaneous values for parameters are available.

The efficiencies of the major powertrain components in the model vary with vehicle speed. The model determines the component efficiencies corresponding to the instantaneous vehicle velocity and calculates the overall powertrain efficiency by multiplying the efficiencies of each component in series. Figure 13 gives an example of the procedure of a single-battery electric vehicle containing an automatic transmission. The overall powertrain efficiency for each time increment is used to transform road-load requirements to storage-system power and energy needs.

For all performance levels except minimum, we used the J227a(D) driving cycle shown in Fig. 14. During this 122-s cycle, the vehicle reaches a maximum speed of 72 km/h (45 mph) and covers a distance of 1.5 km (0.95 mi). We selected the J227a(D) driving cycle for a number of reasons:



Overall drive-train efficiency = $\eta_{DT} = \eta_C \cdot \eta_M \cdot \eta_{TC} \cdot \eta_T$

FIG. 13. Vehicle model application - battery/electric vehicle with automatic transmission.

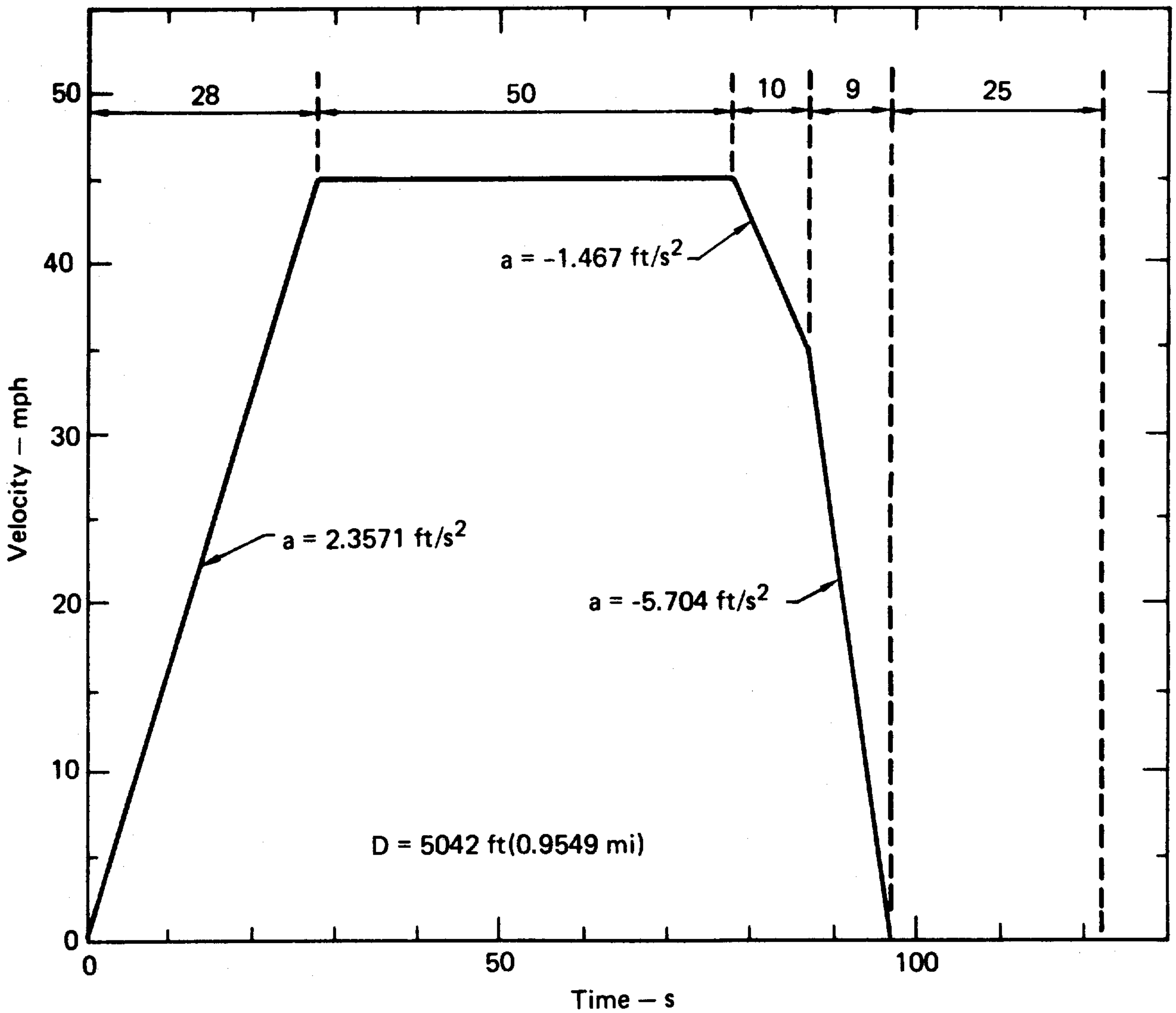


FIG. 14. The Society of Automotive Engineers J227a(D) driving cycle as used in modeling calculations.

- It is analytically simple. Closed-form power and energy equations are easily obtainable.
- It is an urban/suburban start/stop cycle, roughly corresponding to the type of use projected for limited-range energy-storage vehicles.
- The peak-power required (0.016 hp/lb) ensures that the vehicle will be capabile of operating on urban highways at highway speeds.

For minimum performance we used the J227a(C) driving cycle shown in Fig. 15.

Optimization of Battery Characteristics

For all generic battery systems, there are design tradeoffs to be made between short-term peak-power capacity and battery energy capacity. Generally a battery can be designed for high peak-power capability with some loss of energy content or it can be designed for maximum energy content with some loss in peak-power capability. The extent and form of this tradeoff varies for each battery type. The Electrochemical Panel estimated the relationship between short-term (15- to 30-s) specific peak power at a battery's 80% discharge point (P_{M80}) and the specific energy at the 3-h discharge rate ($E_{C/3}$) for each of the secondary battery types evaluated. Using this relationship and other assumptions to facilitate its use in our analysis model, we calculate for a particular vehicle-performance level a minimum vehicle mass by optimally adjusting P_{M80} and $E_{C/3}$ according to the above relationship. In effect the battery is optimized so that it runs out of energy and peak power simultaneously at the 80% discharge point in every case.

To analyze battery-only vehicles, we independently calculated the energy content and peak-power needs of the propulsion battery. We determined battery energy needs principally by the vehicle range requirements. We determined battery short-duration peak-power needs by the vehicle's maximum acceleration requirements using vehicle peak-power-to-mass ratio as a surrogate.

To determine the energy needs of a propulsion battery, we first calculated the battery's average power level for a specific driving pattern. This simplified the calculational procedure. The energy capacity of most batteries varies with the discharge rate, and thus for vehicles the energy capacity of a battery varies with the average sustained power required for a particular driving pattern. Once the average power level over a particular driving cycle

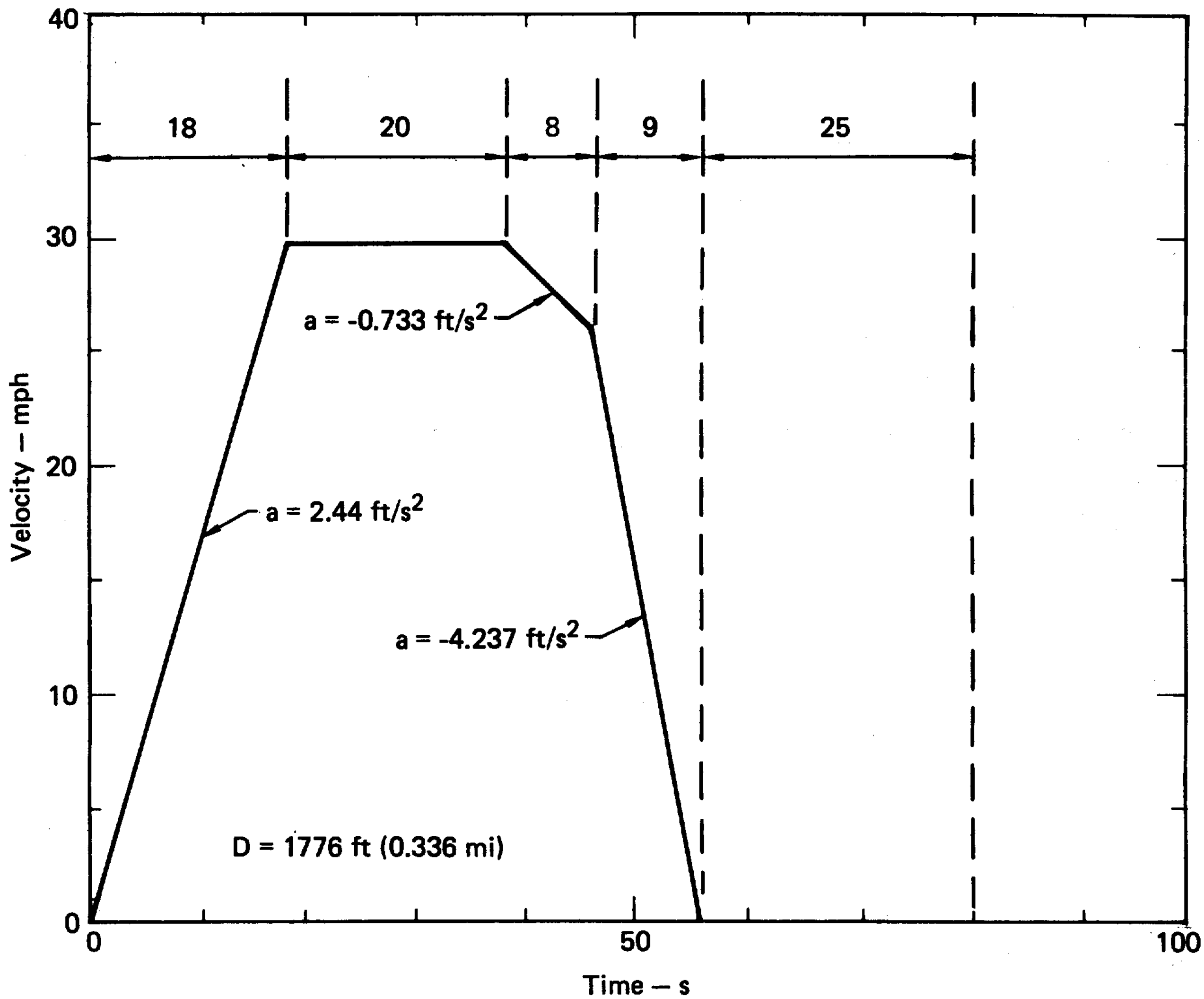


FIG. 15. The Society of Automotive Engineers J227a(c) driving cycle as used in computer models.

is known, the energy capacity of the battery can be determined using the specific-power vs specific-energy relationship for the particular battery (Ragone curve). We assume that this relationship is for practical purposes linear for average discharge rates in the area of interest, i.e., less than the 2-h rate and greater than the 5-h rate. We express this relationship as a straight line having the form:

$$\overline{P}_{avg} = M\,\overline{E}_{avg} + C\ , \tag{3}$$

where M is the slope of the line that is assumed unvarying for each battery type. This equation describes, within the stated limits, the sustained power/energy relationship of a single battery of a given generic type. However, this relationship will be modified by different battery designs within the generic family.

Battery peak-power requirements are determined from the peak-power-to-mass ratio specified for the vehicle, which is measured at the output of the propulsion motor. The criteria we used requires the battery to supply this power level for short periods (15 to 30 s) until the battery reaches its 80% discharge point. Battery peak power is related to the energy content of the battery. We assume that in the region of interest (P_{M80}) it is linearly related to $E_{C/3}$ by Eq. (4). We chose $E_{C/3}$ because the sustained average power required for many automotive applications falls near the 3-h rate. Thus

$$\overline{P}_{M80} = M_1\,\overline{E}_{C/3} + C_1\ . \tag{4}$$

The region of linearity for this equation is bounded by limiting the values of P_{M80} and $E_{C/3}$. The limiting values and the values of M_1 and C_1 were estimated by the Electrochemical Panel. These values are given in Table 14. To design the optimum battery Eqs. (3) and (4) must be solved simultaneously. We did this to obtain the P_{avg}/E_{avg} curves. An example of the results is shown in Fig. 16, where we note changes in the Ragone characteristics for three Ni/Zn batteries designed for different values of short-term peak-power capacity. As specific peak power increases from 150 W/kg to 250 W/kg, the specific energy at the 3-h discharge rate decreases from nearly 70 to approximately 47 Wh/kg. These characteristics are based on the Ni/Zn forecasts for the most probable values in the 1980 to 1985 time period.

TABLE 14. Battery constants and limiting values.

Battery type	Time period	Confidence level	Limits $E_{C/3}$, Wh/kg	Limits P_{M80}, Wh/kg	Battery Constants M_1	Battery Constants C_1	Battery Constants M
Pb/acid	1980-85	Optimistic	56	130	-2.2	178	-0.70
		Probable	50	130		154	-0.73
	1985-90	Optimistic	61	130		214	-0.72
		Probable	55	130		196	-0.68
	1990-2000	Optimistic	68	130		235	-0.75
		Probable	60	130		206	-0.73
Ni/Fe	1980-85	Optimistic	69	200	-3.0	310	-1.80
		Probable	64	200		267	-1.63
	1985-90	Optimistic	78	200		353	-1.67
		Probable	67	200		292	-1.80
	1990-2000	Optimistic	89	200		397	-1.93
		Probable	74	200		325	-1.53
Ni/Zn	1980-85	Optimistic	85	310	-4.51	483	-1.83
		Probable	78	310		441	-2.13
	1985-90	Optimistic	95	310		543	-1.69
		Probable	85	310		478	-2.33
	1990-2000	Optimistic	100	310		590	-2.87
		Probable	92	310		501	-1.58
Na/S(ceramic)	1985-90	Optimistic	130	200	-1.8	309	-0.62
		Probable	110	200		262	-0.60
	1990-2000	Optimistic	150	200		356	-0.60
		Probable	135	200		314	-0.65
Na/S (glass)	1985-90	Optimistic	124	250	0.1	212	-7.67
		Probable	118	230		191	-7.27
	1990-2000	Optimistic	130	300		263	-8.13
		Probable	123	250		212	-7.67
Zn/Cl_2	1980-85	Optimistic	115	175	-2.2	340	-2.47
		Probable	105	175		293	-2.20
	1985-90	Optimistic	125	175		381	-2.29
		Probable	112	175		331	-1.98
	1990-2000	Optimistic	135	175		414	-2.13
		Probable	115	175		351	-1.80
$LiAl/FeS_2$	1985-90	Optimistic	145	210	-2.1	377	-1.00
		Probable	135	210		346	-0.61
	1990-2000	Optimistic	160	210		444	-0.80
		Probable	145	210		382	-0.60

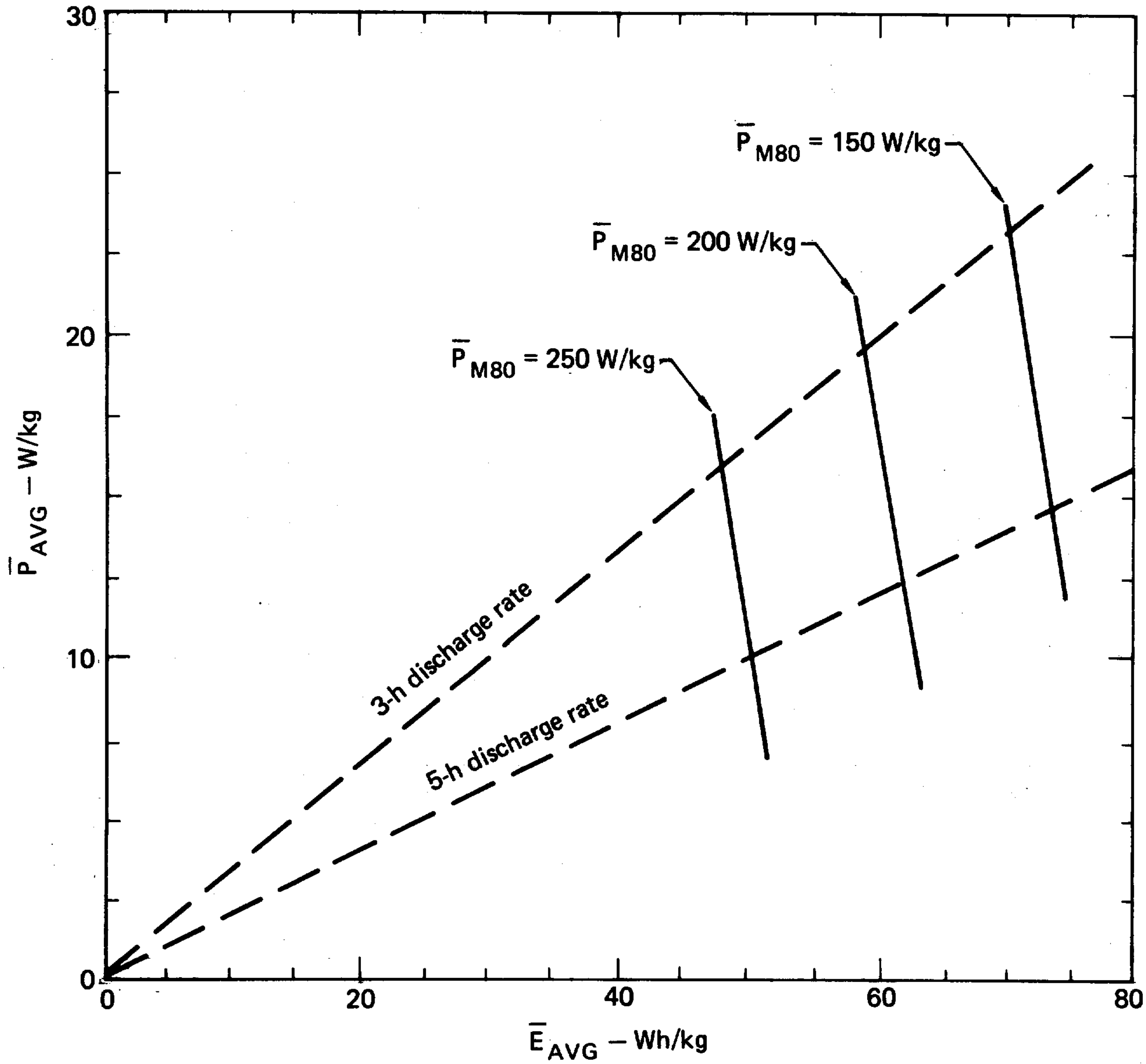


FIG. 16. Changes in specific power vs specific energy as a function of short-term specific peak power for Ni/Zn batteries, 1980-1985 time period, most probable values.

A third equation can be derived that specifies, within battery limits, the optimum value of $E_{C/3}$ (and thus P_{M80}) for any specified combination of electric-vehicle range and power-to-mass ratio. This equation is derived by equating the battery mass required to meet the vehicle's power-to-mass specification to the battery mass required to meet the vehicle's range specification. The following equation is applicable for any driving cycle:

$$\bar{E}_{C/3} = \frac{C_1}{\left\{\dfrac{(P/m)m_t\eta_{avg}(1/3 - M)}{E_{RL}\eta_{M/CPK}\left[\frac{1}{t} - 1.25M(R/RC)\right]}\right\} - M_1}, \qquad (5)$$

where C_1, M_1, and M are battery constants,

(P/m) = specified vehicle power-to-mass ratio as measured at the output of the electric traction motor (W/kg),

m_t = total mass of vehicle (kg),

η_{avg} = average power-train efficiency for the particular drive cycle,

E_{RL} = road-load energy required for one drive cycle (Wh),

$\eta_{M/C\ PK}$ = peak motor/controller efficiency,

t = time required to traverse one drive cycle (h),

R = specified range of vehicle measured at the 80% discharge point (km),

Rc = range traveled over one drive cycle (km).

In addition to the optimization procedure for minimizing the mass of the battery for a particular combination of peak power and range requirement, the analysis takes into account the variations of specific energy with energy-storage capacity. This further refines the analysis so that the characteristics of smaller vehicles reflect more accurately the effect of scaling down the size of the battery. This is done by letting

$$\bar{E}^*_{C/3} = y\bar{E}_{C/3} , \qquad (6)$$

where $\bar{E}_{C/3}$ is the nominal battery specific energy at the 3-h discharge rate, $\bar{E}^*_{C/3}$ is the reduced specific energy, and y is a coefficient less than unity defined by

$$y = a + b\ (1-e^{-ck})\ . \tag{7}$$

In Eq. (7) a, b, and c are constants defined in Volume 2 and k is the total gravimetric storage capacity of the battery.

Technical Analysis

Using representative vehicle data, vehicle-performance specifications, and the above methods of analysis, we were able to determine the mass of energy-storage vehicles by means of iterative computational procedures. The specifics of this process change with the type of energy-storage system being analyzed, but the general procedure remains the same and is shown in Fig. 16.

Our first step is to assume an initial total vehicle mass (W_T), since the peak power and energy content required of the storage device depend upon the total vehicle mass or test mass (assumed equal to vehicle curb mass plus 136 kg). Using this assumed mass plus the specified vehicle air-drag coefficient and frontal area, we determine the energy requirements for the energy-storage propulsion system over the specified driving cycle. In some cases these requirements can be calculated with one or more relatively simple equation. In other cases (e.g., that of battery systems with regenerative braking) they are obtained by repeated numerical integration over the driving-cycle velocity profile. For all cases the efficiencies of the propulsion components are used to transform road-load power and energy into energy storage needs. The peak power requirement of the storage device is determined by the peak-power-to-mass specification for the particular performance level.

Once we know the power and energy needs, we can calculate the mass and volume of the energy-storage propulsion system, using the specific energy and specific power of the storage device and the masses of its power-train components.

At this point we use the mass and volume analysis procedures to determine the change in vehicle curb mass due to the mass and volume of the new energy-storage propulsion system. The vehicle's new and old test masses are compared, and if they are within 5 kg of each other the vehicle's new parameters are accepted and the program ends. If the masses differ by more than 5 kg, we repeat the process until the new and old masses agree.

The programs include checks to ensure that the masses and volumes do not exceed predetermined levels. Vehicle curb mass is not allowed to exceed 2.5 times the baseline vehicle mass shown in Table 2. The vehicle volume change is transformed into a change of vehicle length, and the vehicle length is not allowed to exceed 1.5 times the length of the baseline vehicle.

The actual analysis procedures are considerably more involved than the flow chart in Figure 17 indicates. For example, battery-propelled vehicles with regenerative braking are analyzed by an additional computer algorithm that is initiated on detection of vehicle decelerations. The algorithm calculates the energy available for recovery (kinetic energy less road losses), and reduces the available energy according to the propulsion-system efficiencies. It then determines the state of charge of the battery, constrains the recharge power level not to exceed the maximum allowable battery recharge rate, and further reduces the energy according to the particular battery's recharge efficiency. Finally it adds the remaining regenerative energy to the battery energy register.

For vehicles with multiple power systems, grade requirements, regenerative braking, and power flows between storage devices or from heat engines to storage devices the basic procedure is further complicated. Both the detailed computations and the analysis algorithm become considerably more complex. As an example, Fig. 18 shows the analysis-procedure flow chart for battery/flywheel hybrid vehicles.

Cost Analysis

Purchase costs and total life-cycle costs were calculated for the baseline ICE vehicles and the energy-storage vehicles. The same methodology was used for both. Thus the results should provide a reasonable picture of relative costs. The generalized steps in the methodology were as follows:

- The vehicles were subdivided into components, including both propulsion and nonpropulsion items. The sum of the component costs determined the purchase price of the vehicle.
- Component costs were described by equations relating cost to a performance parameter, such as peak power or mass. The component cost equations were either statistically derived, estimated by the Energy Storage Panels or industrial sources, or developed by comparison

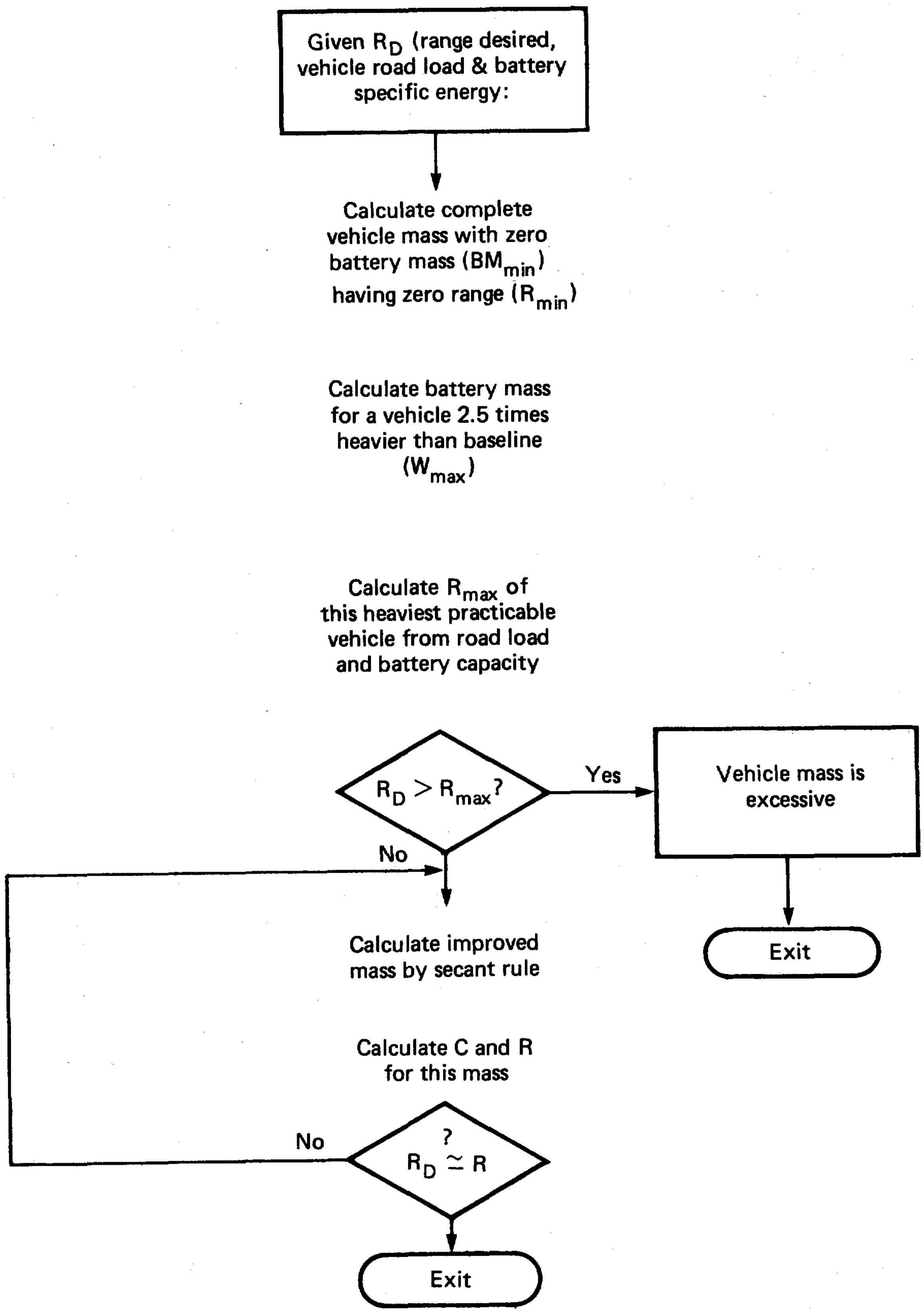


FIG. 17. Flow diagram of analytic procedure for energy-storage vehicles.

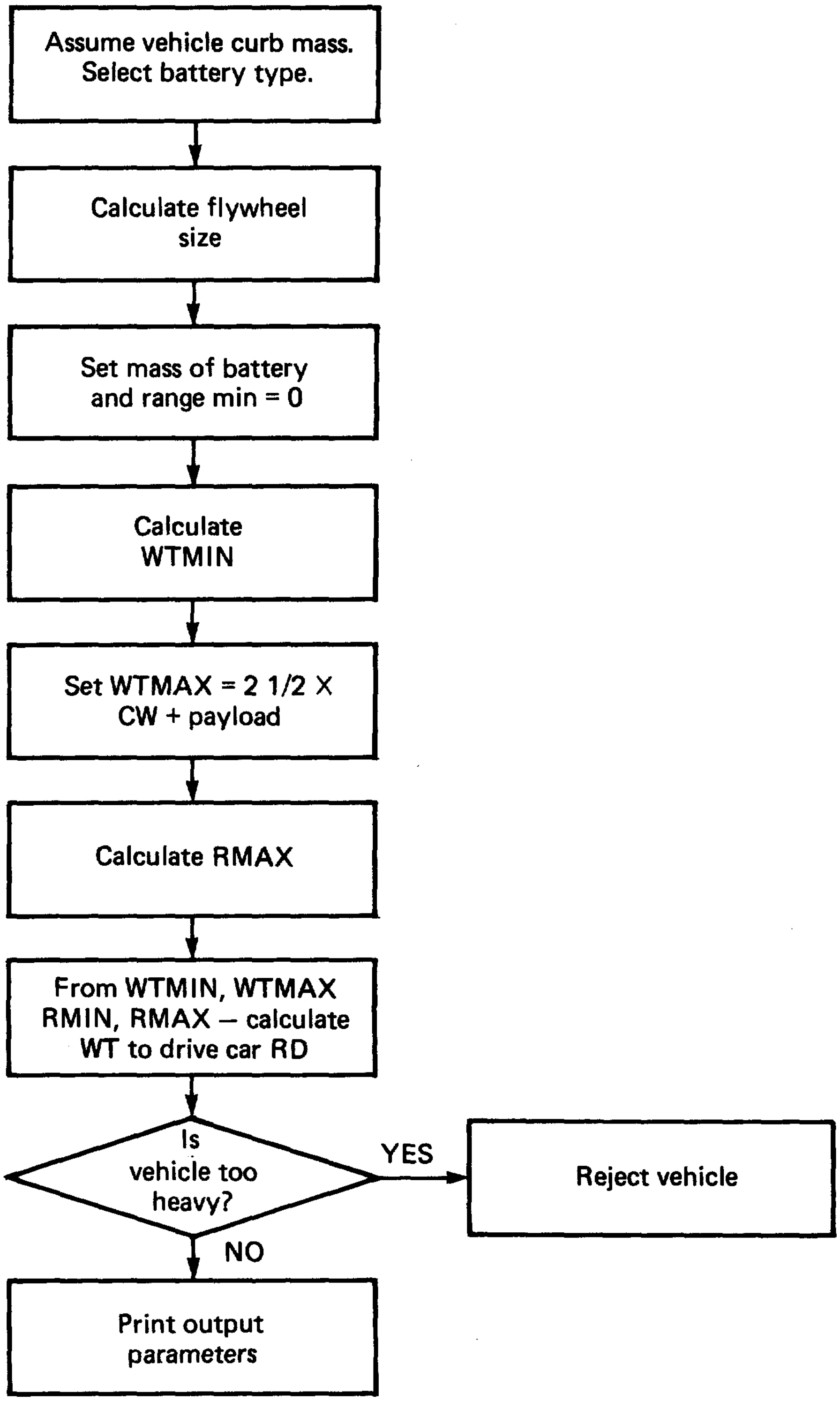


FIG. 18. Analysis of battery/flywheel vehicles.

with similar components presently in production. Where estimates could not be obtained directly, engineering designs were postulated and the component costs estimated by one of the above methods.

- The vehicle performance and mass data used for the cost analysis were taken from the results of the technical analysis described above.
- Vehicle-performance parameters were used to derive the costs of vehicle operation. These costs include the cost of fuel, repair, maintenance, insurance, replacement tires, replacement batteries, and lubricating oil. Costs of system-specific components such as battery chargers were also included where appropriate.
- Annual operating costs were calculated. Where capital costs were incurred such as for replacement batteries, costs were annualized through a calculation procedure sensitive to the opportunity cost of money, the life of the component, and the component salvage value.
- The purchase costs are annualized via a calculation sensitive to the opportunity cost of money, vehicle life, and end-of-life salvage value.
- The annualized initial user and annual operating costs were summed to obtain the total annual life-cycle cost to the user. The annual costs were converted to a cost per km for each specific vehicle.

The following assumptions were made in the cost and mass calculations or in deriving the cost and mass relationship equations:

- The life of all vehicles is 10 y.
- The annual vehicle mileage is 16,000 km.
- The component costs given by the energy-storage panels are assumed to be either dealer or manufacturer costs.
- The capital cost discount rate is 6% for all time periods.
- Vehicles are produced in quantities of no less than 100,000 units per year. The production lasts long enough that costs reflect the full benefit of learning-curve predictions.
- Material costs remain constant for all time periods.
- All costs are in 1977 dollars. This was done because inflation rates beyond the average inflation rate existent between 1978 and the date of this report are too unstable.

- We compared the computed and actual retail costs of vehicles marketed in 1977. The comparison indicated that the cost per unit mass increases for small vehicles. We therefore derived a nonlinear markup factor to fit actual retail cost data for vehicles that cost less than \$3100. For vehicles over \$3100, a 30% markup remains a good approximation to retail vehicle costs. The equation used for vehicles under \$3100 is:

$$\text{Dealer markup} = \frac{160}{(\text{Mfg cost})^{0.6}} .$$

Figure 19 shows a plot of calculated vehicle costs vs curb mass overlaying a scatter diagram of suggested retail costs for actual nonspecialty American-made vehicles with automatic transmissions. The plot of calculated cost data is a smooth curve connecting our calculated retail costs for 15 of the vehicles in the figure.

- Provision was made in the cost analysis for the assignment of salvage values appropriate to the vehicle less the energy-storage system and to the energy-storage system itself, thus permitting the cost benefits of durable systems to be incorporated.
- Battery manufacturing costs are based on \$/kg. This was to account for design variations made in the vehicle simulations that trade specific power for specific energy while maintaining an overall battery size and mass.
- Electric-vehicle repair- and maintenance-cost estimating formulas reflect recently published vehicle-fleet experience.
- The cost analysis reflects the gasoline and electric-fuel cost projections of the Carter National Energy Plan, which is used to facilitate life-cycle costs comparisons. However, these cost projections of fuel are obviously not in accordance with reality. Since the future cost of energy is highly controversial, the derivation of realistic fuel costs lies beyond the scope of this report. Consequently it was elected to parametrically analyze a few baseline and energy-storage vehicles to illustrate the effect of increasing fuel costs on comparative life-cycle costs.

In general the fuel cost/y portion of the life-cycle cost is a linear function of the fuel efficiency of a specific vehicle and the price of fuel.

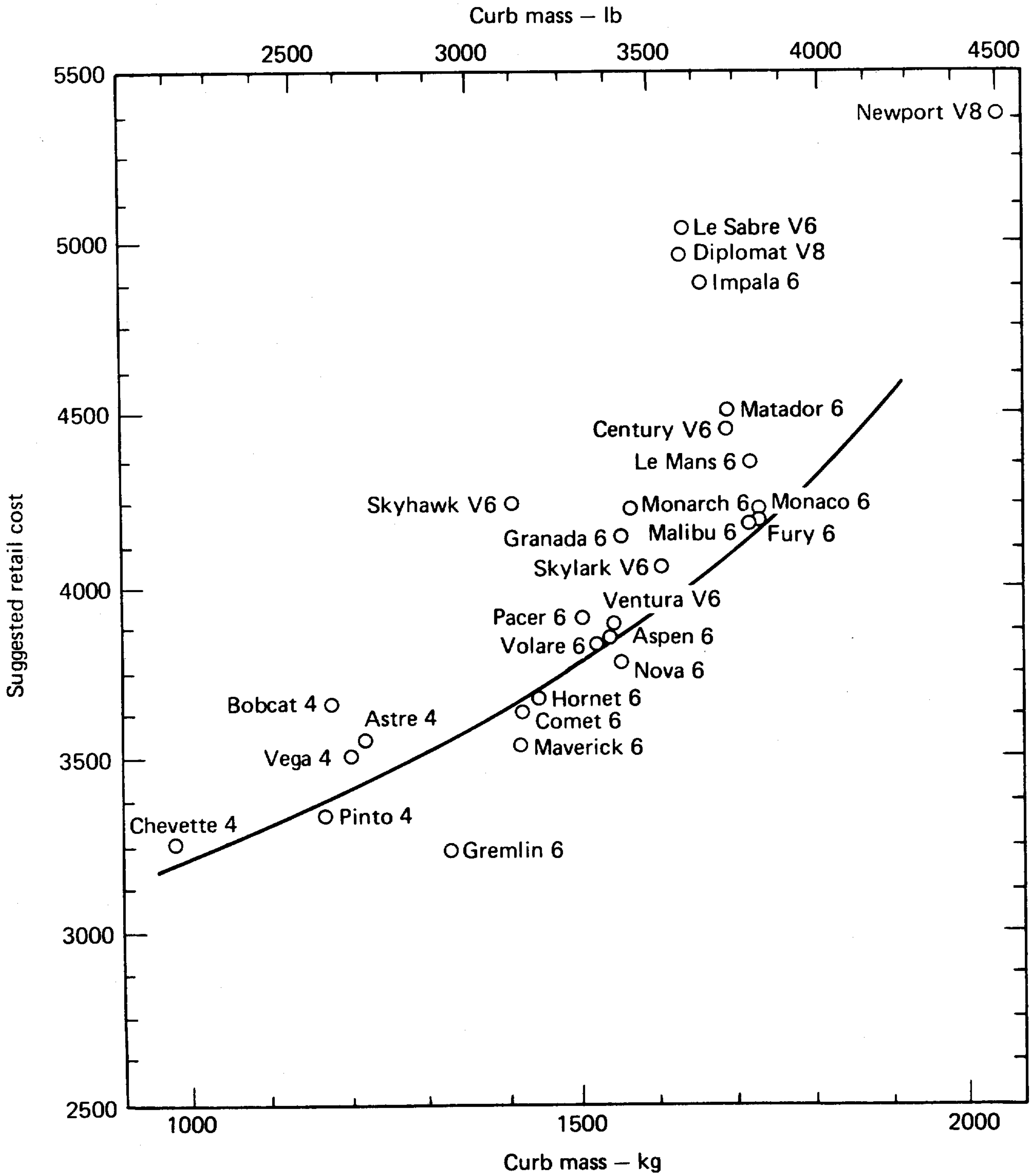


FIG. 19. Curb mass vs suggested 49-state retail cost for selected nonspecialty American-made vehicles with automatic transmissions and overlaid calculated costs. (Source: Automotive News, 1977 Market Data Issue.)

Thus calculating life-cycle cost increases because of increasing fuel cost is a simple matter if these two factors are known. As an example it can be shown that the life-cycle costs for the 1990-2000 versions of the limited-performance Ni/Zn vehicle and the equivalent-performance ICE vehicle are roughly equal at $2.00/gal gasoline cost and 5¢/kWh electric fuel cost. Volume 2 goes into this in more detail.

- Fuel-cost/km calculations include charging-efficiency losses for EVs.
- All vehicle-cost procedures can select from different body-construction technologies.

EXAMINATION OF RELATED ISSUES

During this three-year study the various energy-storage devices were:

- Investigated
- Projected into the future
- Analyzed as propulsion systems and vehicles
- Examined for cost
- Compared with each other and with the ICE.

These analyses have been described briefly in this volume and later some results are shown. However, a number of related issues have also been investigated. These issues are, in general, much more subjective than the analyses thus far described, but add depth to our understanding of the problems.

MARKET PENETRATION AND ENERGY IMPACT

To effectively conserve national petroleum resources, ESVs must capture a significant share of the automobile market. Therefore market penetration and energy-impact analyses were conducted to determine how the introduction of ESVs between now and 2000 could affect petroleum imports and domestic crude consumption.

Technical analysis shows that the energy-storage devices under development can be used to produce automobiles for any of the specified performance levels. The mass and cost of these vehicles will vary with the level of performance required, the type of propulsion system used, the energy-storage device employed, and the year of introduction.

All of these factors will affect the demand for such vehicles in the future. We are interested in the energy-storage propulsion systems and storage devices whose development will lead to the largest reduction in petroleum demand.

Two automobile scenarios were chosen for the market-penetration analysis. Case 1 determined the effect of the introduction of specific-mission electric vehicles.

Case 2 examined the effect of the introduction of these specific-mission vehicles in combination with general-purpose (ICE equivalent) vehicles.

To determine the possible reduction in petroleum demand, long-range forecasts of market penetration were prepared in terms of annual vehicle kilometers traveled (VkmT) by the automobiles in Cases 1 and 2. Such demand forecasting is difficult. The projections must be based on assumptions and limited vehicle-use data bases. Projections were done for a business-as-usual environment where price variations are gradual and no critical shortages occur.

Using these guidelines it was found that in Case 1, specific-mission EVs should account for 2.2% of the automobile sales market in 2000. This percentage should increase slightly to 2.5% by 2025. This translates to 0.7% of the VkmT in 2000, and 0.8% of the VkmT in 2025.

In Case 2, the availability of general-purpose automobiles was predicted to result in ESV auto sales to account for 16% of the total market in the year 2000 and to 17% in 2025. ESV predicted VkmT should be 13.9% of the total in 2000 and 14.5% in 2025. The increase in both auto sales and VkmT for Case 2 over Case 1 should result from the general-purpose ESVs, since the demand for specific-mission electrics is essentially the same in both cases. The EV 150 (240-km range EV) should be the specific-mission electric vehicle in greatest demand.

These results in terms of VkmT were input to the LLL Energy Policy Model (EPM). The model was then used to calculate the effect of ESVs on future U.S. energy flows.

For Case 1 the EPM calculated that since specific-mission EVs comprise approximately 0.7% of the automotive fleet in terms of VkmT in 2000, the price and quantity of oil imports and domestic crude oil used will be virtually unaffected. The transportation fuel mix will be only slightly affected.

In Case 2, although the price is virtually unaffected, the large number of ESV and the VkmT attributed to them will cause the total import quantity to be reduced by approximately 0.6 quad in 2000. Total domestic crude production and prices are essentially unchanged but there is a total projected displacement of 1 quad of petroleum from the transportation sector in 2000.

In effect, this exercise showed that with business-as-usual conditions (i.e., economic, petroleum supply, etc.), general-purpose energy-storage vehicles are most desirable. Still, the analysis projects a market penetration of ESVs too small to have a major impact on petroleum use. However, even in the few months since this task was completed, changes have taken place that could not have been predicted on the basis of historical data.

We have begun to shift from the technical and cost analysis of energy-storage devices to a better assessment of their future impact. Several issues related to the assessment of future impact have been examined. The first seeks to identify ESV combinations that can satisfy both consumer mobility and national energy goals for transportation. The second examines the effect of manufacturing and service infrastructure requirements on ESV market growth.

EFFECT OF PETROLEUM AVAILABILITY ON ESV MARKET PENETRATION - METHODOLOGY

We are developing a methodology for assessing the relative merits of ESV candidates and their potential penetration into the personal transportation market in the light of specific, foreseeable changes in petroleum availability.

The framework within which the methodology was developed considers that the national economy is like a giant jigsaw puzzle in which each piece of the puzzle is a part of the economy. All the pieces must fit together for the economy to operate successfully. The personal transportation sector is one portion of the puzzle and consists of a tightly integrated interlocking network. For the last 50 y this network has evolved around a single propulsion technology and a single fuel as an energy source. However, this network is coming apart because of the strains imposed by interruptions in fuel supply. The methodology provides a way of examining how the personal transportation sector network can be reassembled around the realities of our energy future and the part that ESVs can play in that network.

The literature abounds with solutions to the transportation sector's puzzle. However, the effectiveness of any of these solutions, e.g., new vehicle types, alternate fuels, and the like, are constrained by the degree to which industry and the public can accommodate change. Before the transportation system can use even the most attractive technologies, it must be able to accommodate them and adjust to them while achieving a smooth transition to avoid industry dislocations and consumer disaffection. Hence, in developing the methodology, careful attention was given to the assumed rate of commercialization of each of the new technologies considered.

Reduction of petroleum demands can be attained either by voluntary cooperation of the public or by law, and both options are currently being pursued. However, for developing the methodology we focused on meeting specific national energy goals for transportation defined by an unspecified government intervention method. This avoided the necessity of presuming what voluntary level of cooperation could be relied on to reach the defined goals. We selected a mechanism that implicitly addressed all elements of the transportation system and explicitly addressed the assumed national energy goal.

Next we defined the boundaries of the interrelated elements of the transportation system. The transportation system must provide individual mobility to the extent needed for the economic and socioeconomic health and stability of the individual and the nation. We have called this mobility requirement essential VMT.

Once having defined the boundaries of the personal transportation system, we then define the elements in the system we feel are parameters of interest.

- <u>Vehicle Technology</u> Identifiable vehicle candidates for integration into the transportation system over the time of interest. Conventional ICE technology is a candidate as well as ESV technologies and ICEs using unconventional fuels.
- <u>Vehicle Characteristics</u> The cost, performance, fuel efficiency, and mission capability of each vehicle class within a vehicle technology. A five-passenger, equivalent-performance, rechargeable-battery vehicle would represent a vehicle class within the technology.
- <u>Transportation-Energy Industry</u> The industry supplying the types of energy required by the vehicle technology.
- <u>Raw-Material-Support Industry</u> The industry supplying the raw materials necessary to construct both the vehicles and the infrastructure required for their support.

- Infrastructure-Support Industry The industries responsible for constructing and maintaining the infrastructure necessary for selling, servicing, and supplying fuel to a vehicle technology.
- Vehicle Manufacturers The industry that constructs and distributes vehicles to the market.
- Consumer Needs The group of requirements defining the transportation and vehicular needs of the consumer.
- Consumer Preferences The consumer preference criteria that affect the choice of vehicle technology and vehicle characteristics.
- Government Support The actions the government must take to foster entry of a new-vehicle technology into the transportation market. This might be government-sponsored research and development or subsidies, either to the consumer or the auto manufacturer.

The limitations of the intervention policy can be used to assess alternate future ESV transportation scenarios by ensuring that such scenarios are consistent with national transportation energy goals, the transportation-system boundaries, and the internal sector elements.

The development of a model to where a vehicle mix (ESV and other) meets the desired petroleum saving goals and other criteria is described in Volume 2 of this report. The effort is continuing.

One of the important factors in the analysis is an understanding of the manufacturing and service infrastructure requirements of ESVs.

MANUFACTURING AND SERVICE INFRASTRUCTURE

The purpose is to examine the manufacturing and service infrastructure requirements for ESVs to see if there are any roadblocks to the introduction of ESVs that are technically and cost attractive.

The approach compared potential growth of ESV production to other industries to obtain limiting constraints on growth characteristics. This required a study of various industries to establish characteristics such as type, rate, and term of growth.

When ESVs become a production item, they will be mass produced just as autos are today. For sustained growth necessary for the ESV to impact the transportation industry, vehicle manufacturers must be as large as present major auto companies to take the lead in ESV production.

Major auto manufacturers have the necessary facilities, plant capacity, labor and management, and the necessary capital to make the changeover to ESV production.

Given that vehicle manufacturers comparable to the major auto companies are involved, vehicle production will at first be limited by availability of components that are unique to the ESV of the electric and hybrid variety such as batteries, motors, controllers, etc., and those unique to the storage and transport of hydrogen for the chemical systems.

Production capacity for controllers, which is an electronic device, can be developed quite rapidly because of minimal startup requirements of capital and equipment. Thus no problem is expected in supplying the number of controllers needed for ESV production.

Electric traction motors may present more of a problem, since no excess production capacity now exists nor do there appear to be any conversion possibilities. Motor-production capacity would need to be developed. It is probable that the vehicle manufacturers would choose to produce their own electric traction motors as they now produce power plants for the ICE vehicles.

Based on the lack of materials and production facilities, batteries appear to be the largest constraint to large-scale ESV production. An average of 14 to 16 heavy duty 6-V batteries per vehicle are used in current experimental EV designs. The production requirements if ESVs are to make a major impact are staggering from an original-equipment basis alone. If replacement is taken into account (three out of four batteries now sold for current ICE automotive use are for replacement) the number of batteries required is even greater.

The service infrastructure was examined by identifying service systems and refueling methods capable of supplying timely and affordable service. The relationships between service systems and refueling methods were also examined. The service systems for rechargeable batteries considered were:

- Home refueling - electrical recharging of batteries is accomplished at the home of the ESV owner.
- Distributed refueling - recharging of batteries through a metered system located at parking lots, shopping centers, roadside stations, restaurants, and theaters.
- Service-facility refueling - a system of service stations similar to those in existence today but retrofitted to service ESVs.

Refueling methods considered were:

- Secondary battery recharge - a storage battery recharged by connection through appropriate controls to an electrical source.
- Secondary battery exchange - a discharged battery pack in the ESV is removed and replaced with a charged battery pack. The discharged battery pack is recharged for later use by another ESV. It is also assumed that battery packs may be recharged without removal from the vehicle.
- Aluminum/air power-cell servicing - the Al/air battery requires periodic additions of aluminum, water, and sodium hydroxide and removal of hydrargillite.
- Hydrogen fuel - hydrogen storage, handling, and supply transport must be considered.
- Hybrid refueling - hybrids use a combination of energy-storage systems, usually rechargeable batteries and a small ICE to provide range extension. Hybrid refueling therefore entails a combination of gasoline and battery recharge, although they need not occur at the same time.

The service infrastructure study using modeling and other techniques is not yet complete. However, some preliminary comments and general indications can be given.

A great advantage of electrical recharging is that a national distribution network now exists. While additional equipment will be required for electrical recharging, the cost would be a small fraction of the cost to establish a national network of battery exchange, Al/air, or hydrogen service facilities. Dual-fueled and power-leveling hybrids enjoy a similar advantage in that a national gasoline distribution system now exists to go with the electrical.

Building a national network of battery exchange, Al/air, or hydrogen service facilities may present difficulties. The capital requirements are quite large when the equipment and construction requirements are considered. The development could be further compounded by a mutually inhibiting condition: People won't purchase ESV because service isn't available, and companies won't develop service facilities because few vehicles demand service.

Facilities for large-volume production of hydrogen do not now exist and would have to be built. A national distribution network must also be developed.

Service Constraints

1. Battery exchange has some serious disadvantages and a question exists as to whether a viable system could be developed.
2. Al/air refueling would require facility changes but no serious problems have surfaced.
3. Hydrogen has supply and distribution requirements. However, the depth and dimension of the hydrogen service constraints remain to be identified.

Preliminary Results

The ability of manufacturing to sustain an accelerated ESV production depends largely on whether ICE-plant capacity is converted to ESV. If new-plant capacity must be built, then ESV production growth will be considerably slower.

Another limiting factor appears to be battery production. Battery production must increase at a faster rate than ESV production, since the needs of both new-vehicle production and the replacement market must be met. Electric motors could be limiting but are considered, at this point, to be less so than batteries.

Historically, the upper bound on long-term compound growth rate of new production is estimated at no more than 40%, with 30% considered to be a more likely figure.

Electrical recharging by home and distributed methods is nearly certain to provide a substantial portion of refueling for EVs using rechargeable batteries. Battery exchange has many obstacles to overcome and it is doubtful that it could be a viable refueling method.

An Al/air refueling system has no problems that appear prohibitive. Given an Al/air power cell that provides superior performance and cost characteristics for ESV, an Al/air refueling system could certainly be developed.

We are not yet prepared to provide conclusions concerning hydrogen service.

Electrical recharging appears to have many advantages over other approaches. An ESV that uses another refueling method will have to show clearly superior cost and performance characteristics.

Finally, a short survey was made of the present-day uses of energy storage in the field of specialty vehicles.

SPECIALTY MARKETS FOR ENERGY-STORAGE VEHICLES

In focusing on energy-storage devices for highway vehicles we sometimes forget that experience has already been gained in the field of specialized vehicles. Lead/acid batteries provide power for about 750,000 golf carts and forklift trucks in the U.S. Other applications range from one-passenger conveyances such as scooters and wheelchairs to huge mining vehicles. The current annual domestic production of these special battery-powered vehicles is about 66,000 units/y.

Other storage systems have also been tried. Compressed-air storage and thermal storage have been used for industrial trucks and locomotives. (So-called fire-less locomotives used the stored energy of pressurized hot water, which flashes into steam as the pressure is reduced.)

Mine locomotives driven by flywheels have been built in Europe, and these were tried in small numbers during the 1950s. These machines had to be recharged at frequent intervals because of limited storage capacities and inefficient energy conversions.

The mining vehicle continues to frustrate design engineers. Diesel power has strong drawbacks when used underground, including exhaust emissions, noise, and heat release. Some rubber-tired vehicles are electrically powered through trailing cables, which severly limit the flexibility of operations. Other machines are battery powered and thus suffer a restricted range between charges; the charging process itself is time consuming. The need for a better energy-storage device is apparent, and points to the need for R&D.

The other specialty vehicles also require improved energy-storage devices. For example, forklift batteries generally need recharging at the end of each shift. The present solution is to change batteries if more than one shift per day is worked.

New markets would open up if improved storage systems were available. Only about 30,000 lawn and garden tractors are now battery powered, but about 500,000 others are powered by ICE. Another potential market is the airport shuttle bus. Such buses have short, predictable routes but operate round-the-clock. Hydrogen storage, if it could be quickly recharged, might lend itself to this use. A hydrogen-fueled ICE would have a clean exhaust and would provide the accustomed levels of performance, without sacrificing such features as air conditioning and heating.

Specialty vehicles provide a reservoir of experience in the technology, operations, and economics of energy-storage propulsion. They also present continuing challenges for the improvement of storage systems.

Specialty vehicles could be considered as appropriate host vehicles for the demonstration and testing of new energy-storage technologies. There is an advantage in doing such testing in a controlled and supervised off-highway environment. Most of the world's viable power systems were first developed to meet the economic and reliability challenges of industrial applications. The diesel engine, for example, was improved for many years in industry before finding its way into trucks and passenger cars.

OTHER RELATED TASKS

In addition to the above, a number of other independent studies were conducted in connection with this work. The results were used by the study team in conducting their evaluation and they are presented in Volume 2 of each year's report, except for the critiques which were published separately.

The independent studies are as follows:

Future heat-engine vehicle systems
Identification of technical barriers to commercialization
Cost and environmental analysis
Social issues in transportation
Safety aspects of advanced vehicles
Electric-motor drive systems for vehicular applications
Evaluation of technical uncertainty
Review and critique of 1977 Study, Vols. 1 and 2
Vehicle demand modeling
Vehicle energy analysis
Critique of 1978 Study, Vols. 1 and 2
Future petroleum consumption by passenger cars in relation to EHVs

RESULTS AND CONCLUSIONS

A number of energy-storage devices and automotive propulsion systems using these devices have been examined. The purpose of the study was to determine which devices and systems are best suited for automotive applications as replacements for petroleum-dependent vehicles. In the process at least the following were considered.

Seven battery systems with and without mechanical-power boosting

Several hydrogen concepts

Hybrid energy-storage coupled with heat engines

The above were installed in various-sized vehicles and projected into three major time frames with two levels of likelihood. This resulted in a large amount of data output. A critical look at this output (Volumes 2 of the 1977, 1978, and 1979 Study) indicates that the data could be reduced without losing major value. In the following pages we will summarize and develop trends from the data.

RESULTS

The results of the end-use analysis will be presented in a minimum number of categories. Since vehicle size does not affect the ranking of systems, all comparisons will be discussed using a five-passenger vehicle. Only the probable case will be discussed here, since optimistic projections were upper bounds, i.e., they are not expected to be exceeded. Many other cases are given in Volumes 2 of the 1977, 1978, and 1979 Study, or can be inspected through the Technology Information System (TIS) available through LLL and/or DOE.

Figures 20 through 31 show the mass, initial cost, and life-cycle cost projections for most of the systems analyzed. The hydrogen microsphere system is projected only in the last time frame under optimistic conditions. All projections involving flywheels are for vehicles having the acceleration of an equivalent-performance vehicle, but having the range indicated on the chart. The dual-fueled hybrids are only considered for equivalent-performance vehicles.

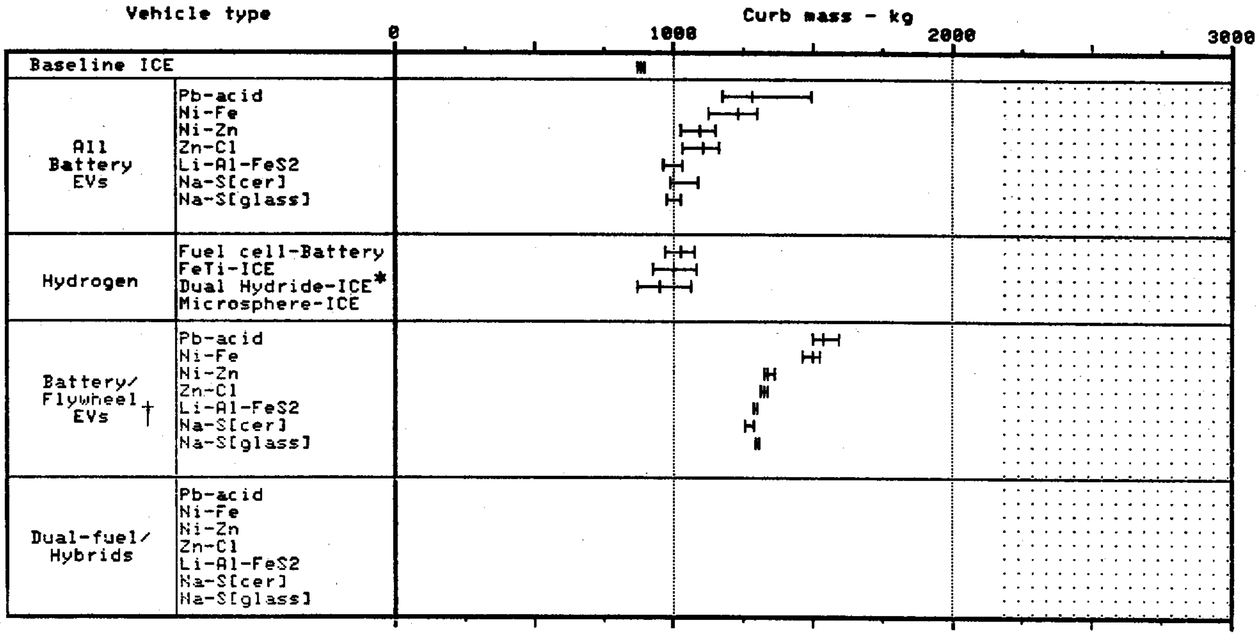


FIG. 20. Minimum performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

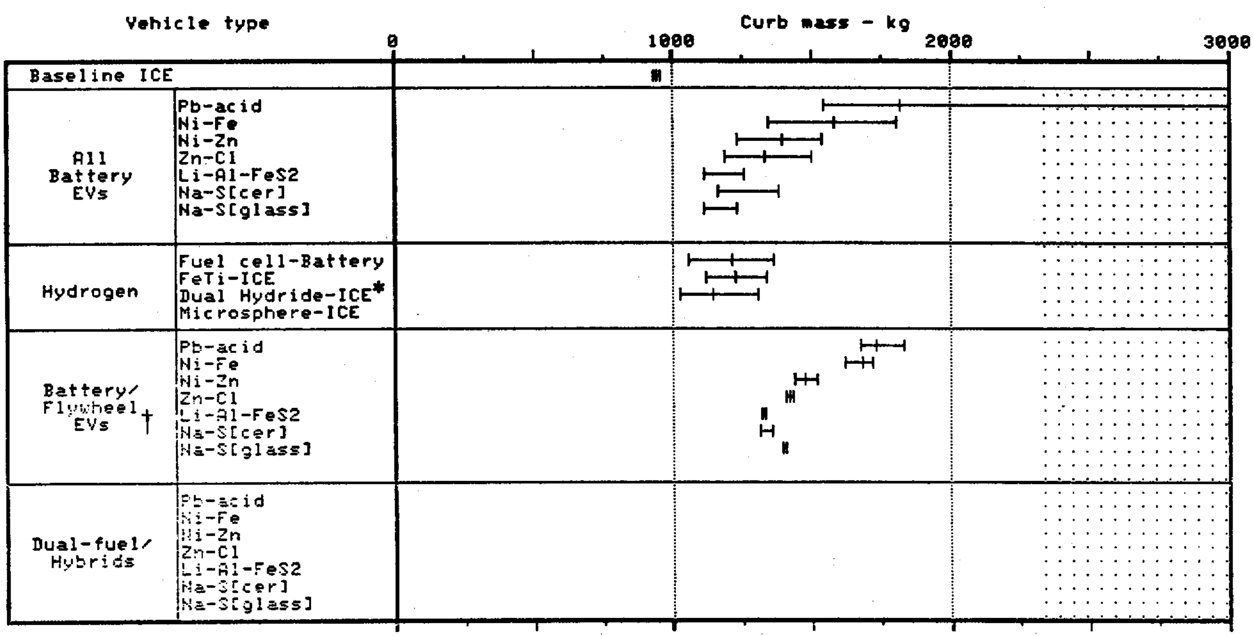


FIG. 21. Limited performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

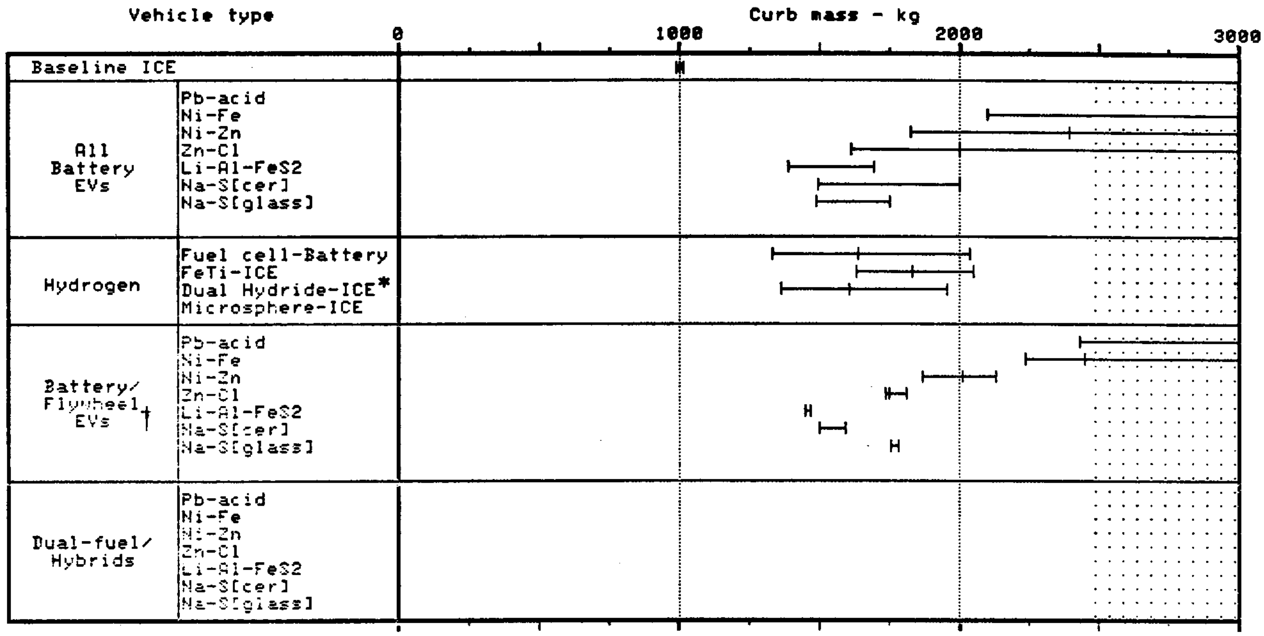


FIG. 22. Intermediate performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

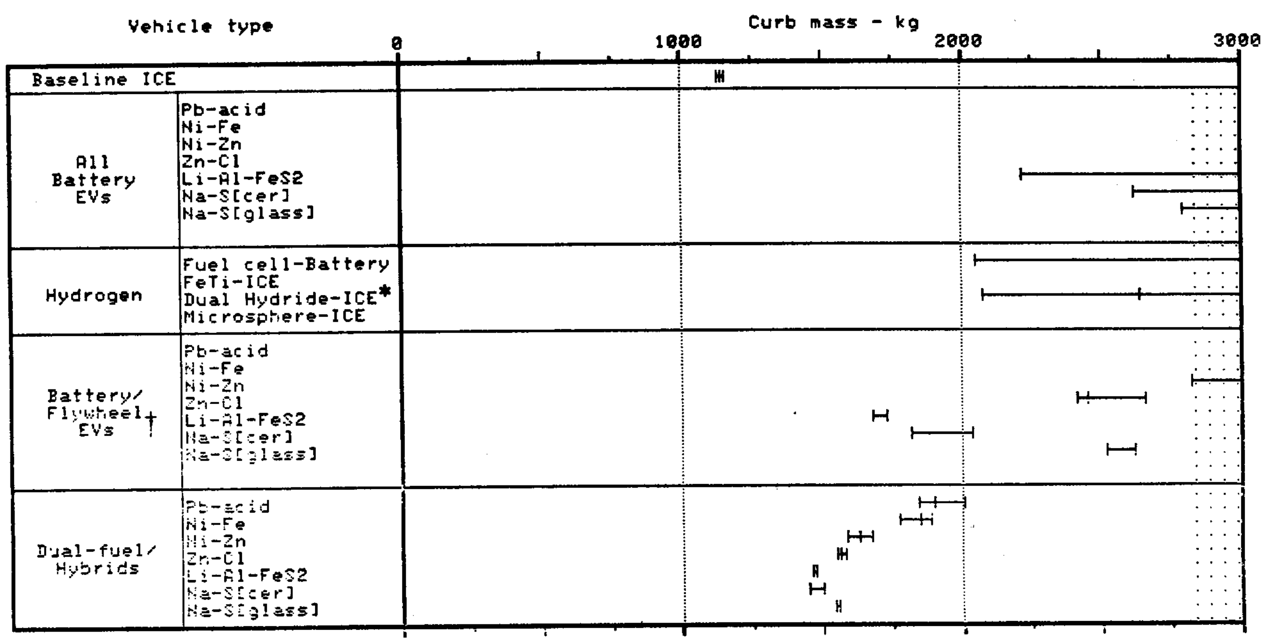


FIG. 23. Equivalent performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

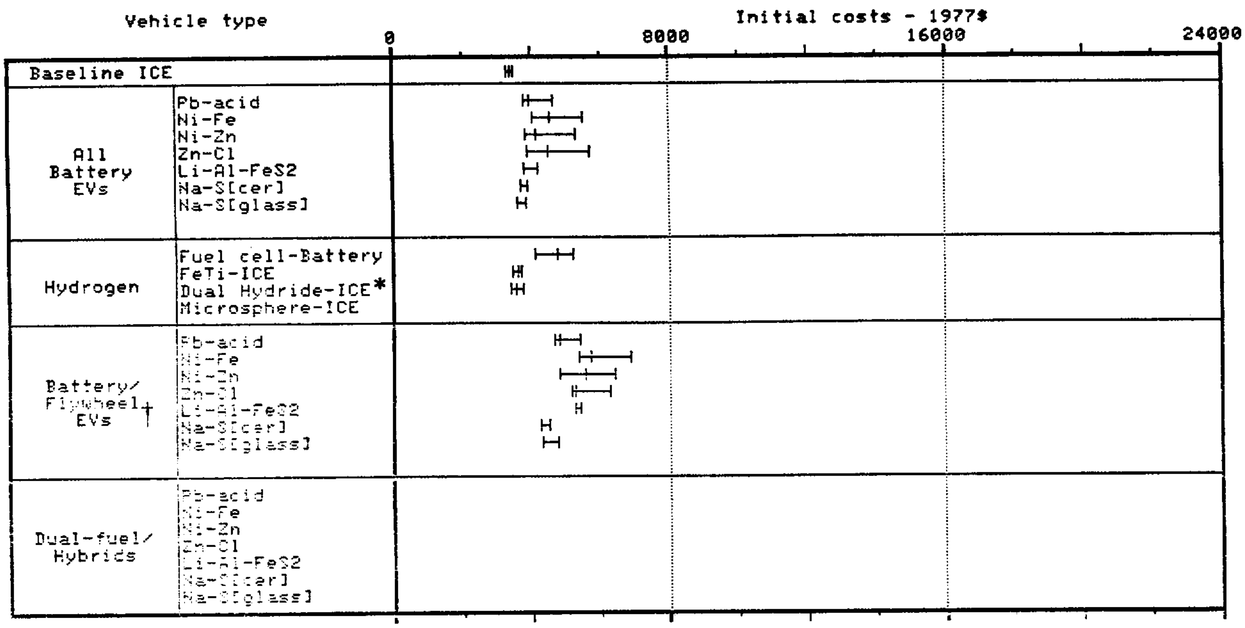


FIG. 24. Minimum performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

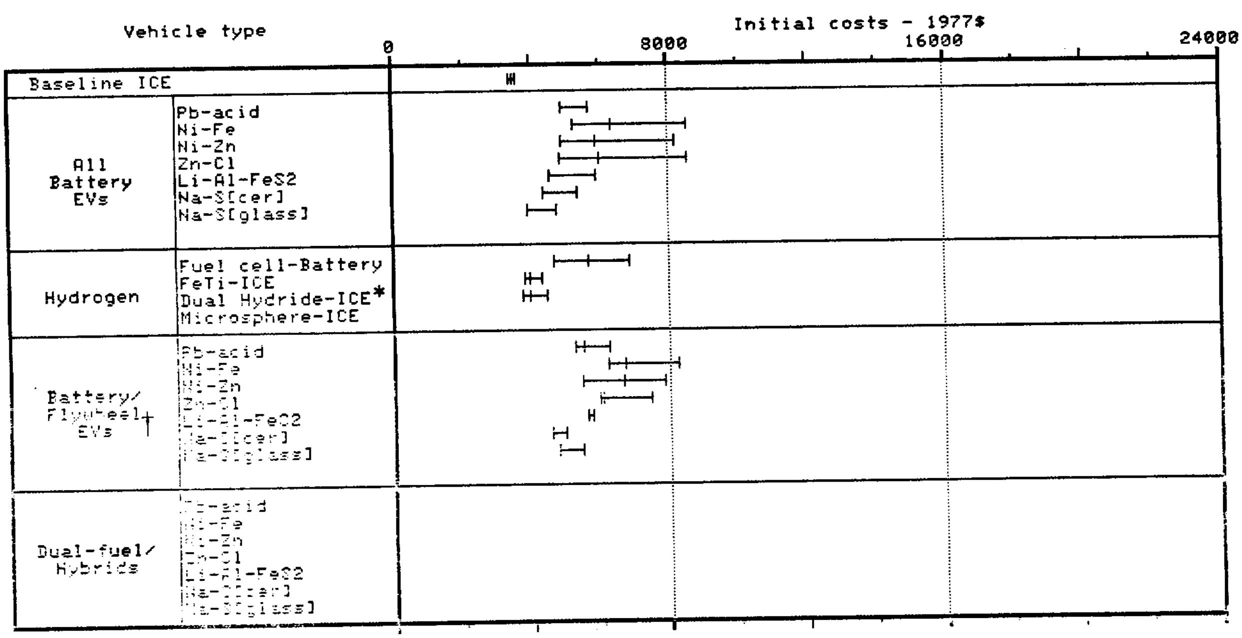


FIG. 25. Limited performance.

* MgHx is combined with FeTi in the dual-hydride system.

† All-battery/flywheel systems exhibit equivalent-level acceleration.

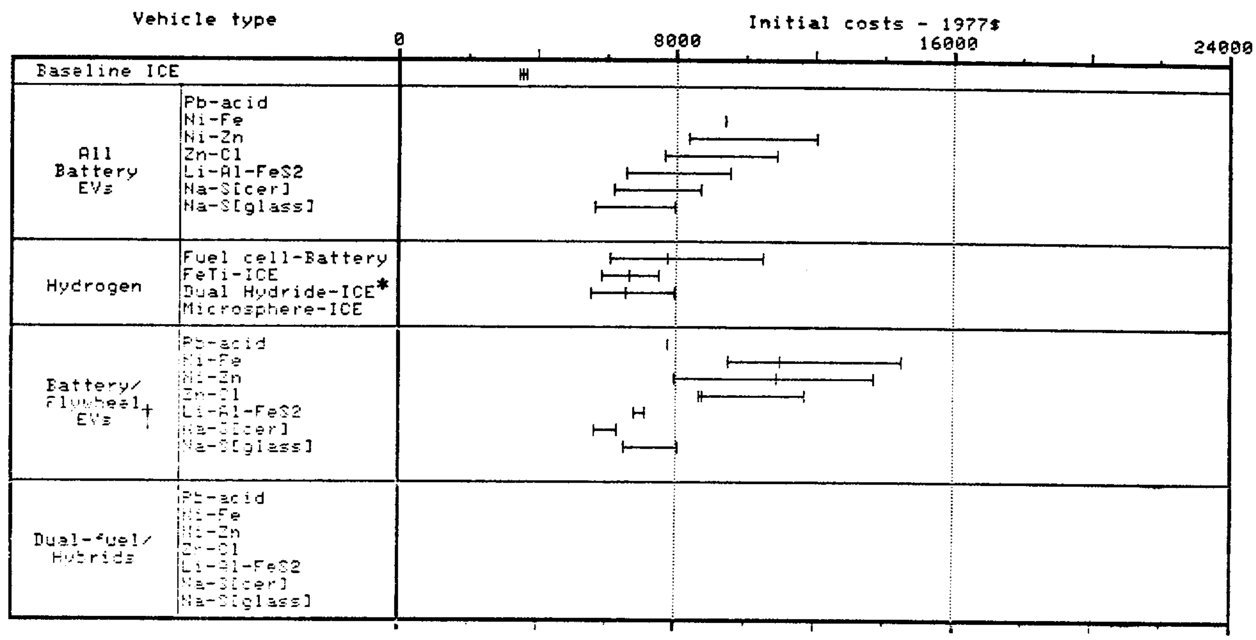


FIG. 26. Intermediate performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

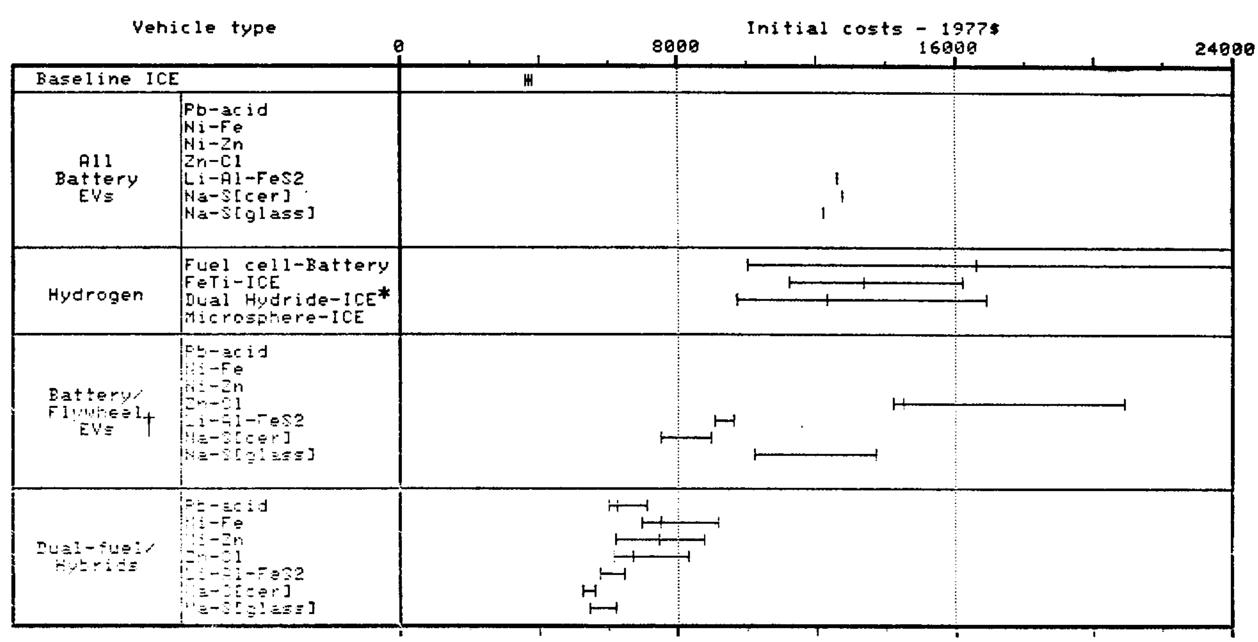


FIG. 27. Equivalent performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

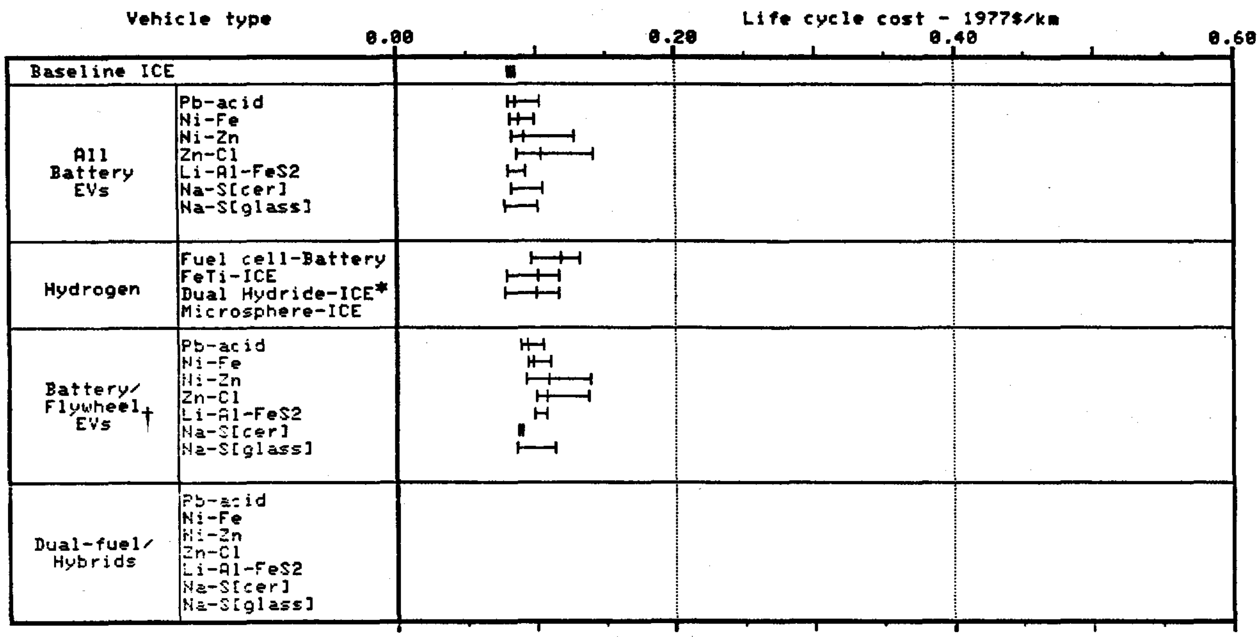


FIG. 28. Minimum performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

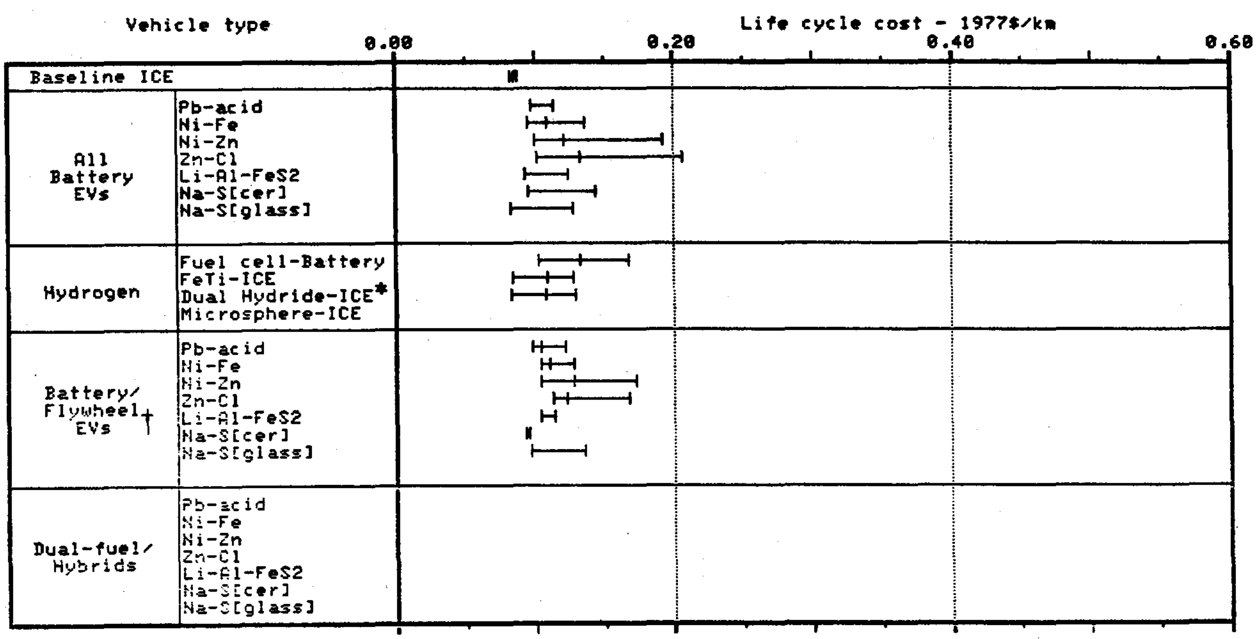


FIG. 29. Limited performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

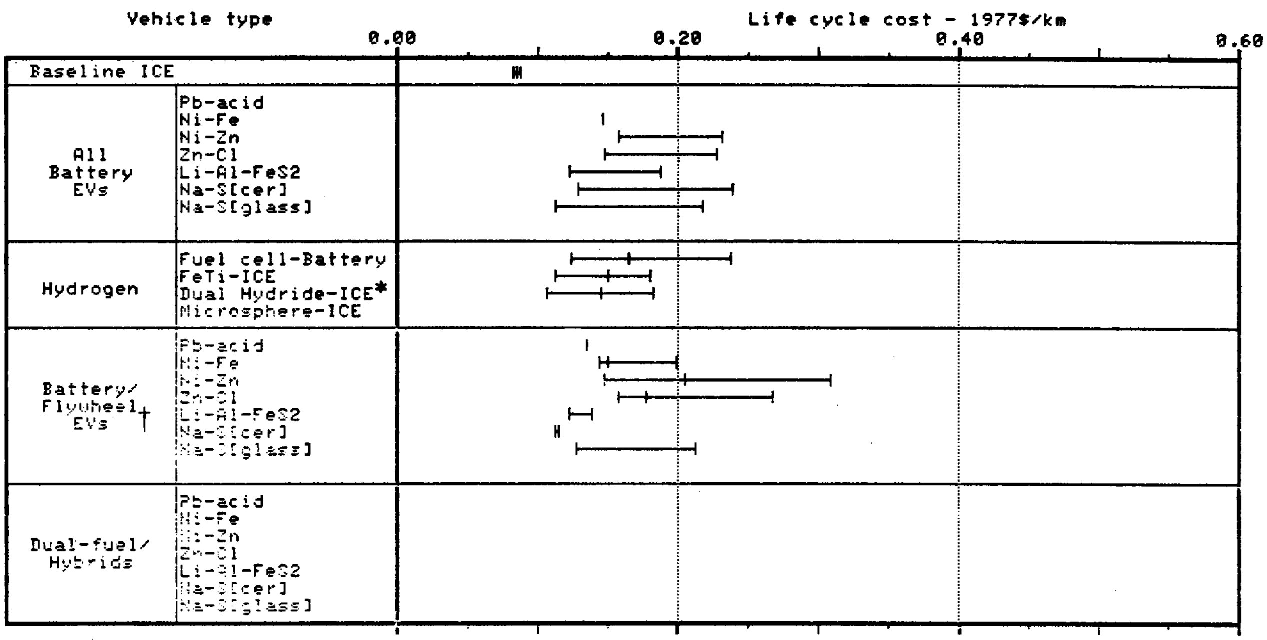


FIG. 30. Intermediate performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

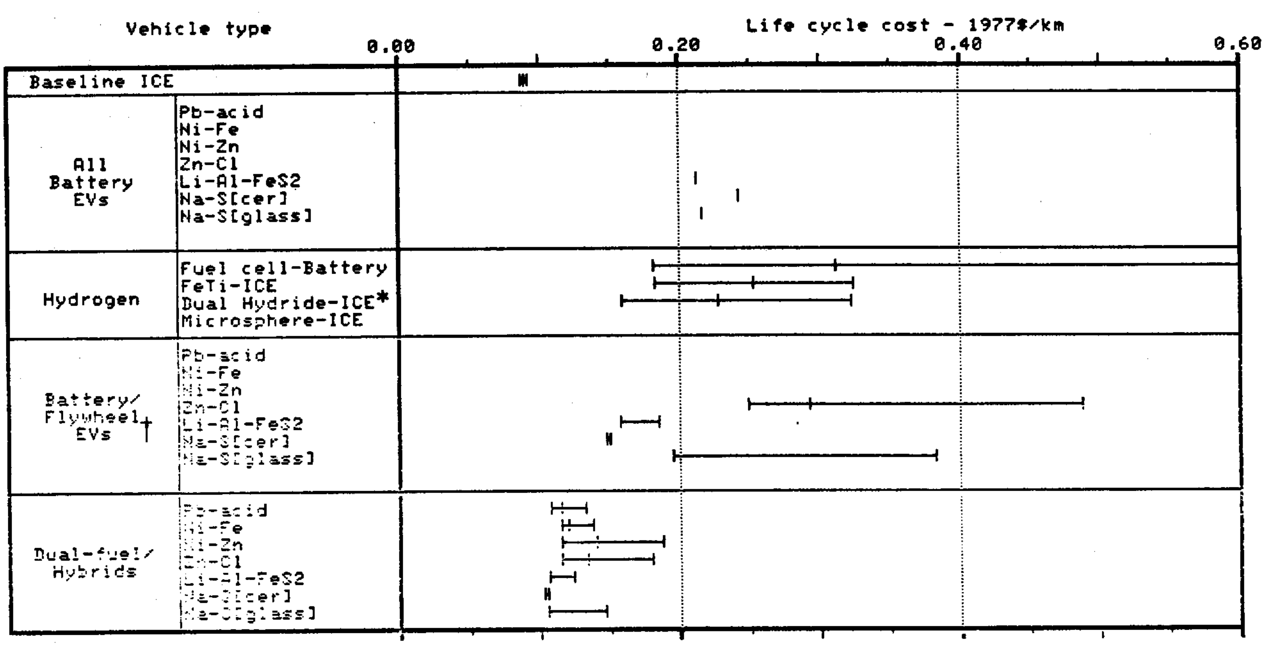


FIG. 31. Equivalent performance.

*** MgHx is combined with FeTi in the dual-hydride system.**

† All-battery/flywheel systems exhibit equivalent-level acceleration.

The charts that follow are a sample set of the projections developed during the study, and were computer generated. Each chart is for a given performance level and shows the projected curb mass, initial cost, or life-cycle cost for each of the systems. The information is presented as a vertical tic mark for a single time period; the lowest mass/cost/LCC are always at the most remote time period.

1980-1985 1985-1990 1990-2000

In cases where the system is not projected to exist (or it's mass is greater than 2.5 times the mass of the ICE base vehicle) the tic mark is missing. In the single case of the hydrogen-microsphere system, projections were made only for the 1985-1990 time frame based on optimistic projections, so no plots are indicated on this subset of the charts.

It was stated earlier that the initial cost and the curb mass were surrogates for systems of equal performance. Figures 32 and 33 illustrate that this is true. In these curves each vehicle type is represented by a single system, e.g., Pb/acid EV is used to represent all-battery EVs, for simplicity. Careful examination of the charts indicates no major problem in doing this. The plots show how curb mass and initial cost vary from 1980-2000 as a function of performance. The first result is that the general location and shape of the projections follow the same pattern for cost and weight corroborating the surrogate relation. Since this relationship appears to hold so well, we will discuss the four levels of performance on the basis of initial cost, Figs. 24-27.

The all-battery EV entries show that in the first time period all-battery EVs are predicted to achieve only minimum and limited performance. Also these systems all cost about the same. The Pb/acid system attains only minimum and limited performance -- but does it at minimum cost. In the second time frame, several new battery systems, $LiAl/FeS_2$, Na/S (cer), and Na/S (glass) become available and begin to surpass the Pb/acid, Ni/Fe, Ni/Zn, and $ZnCl_2$ systems in cost somewhat, but there are no serious contenders in the equivalent-performance range.

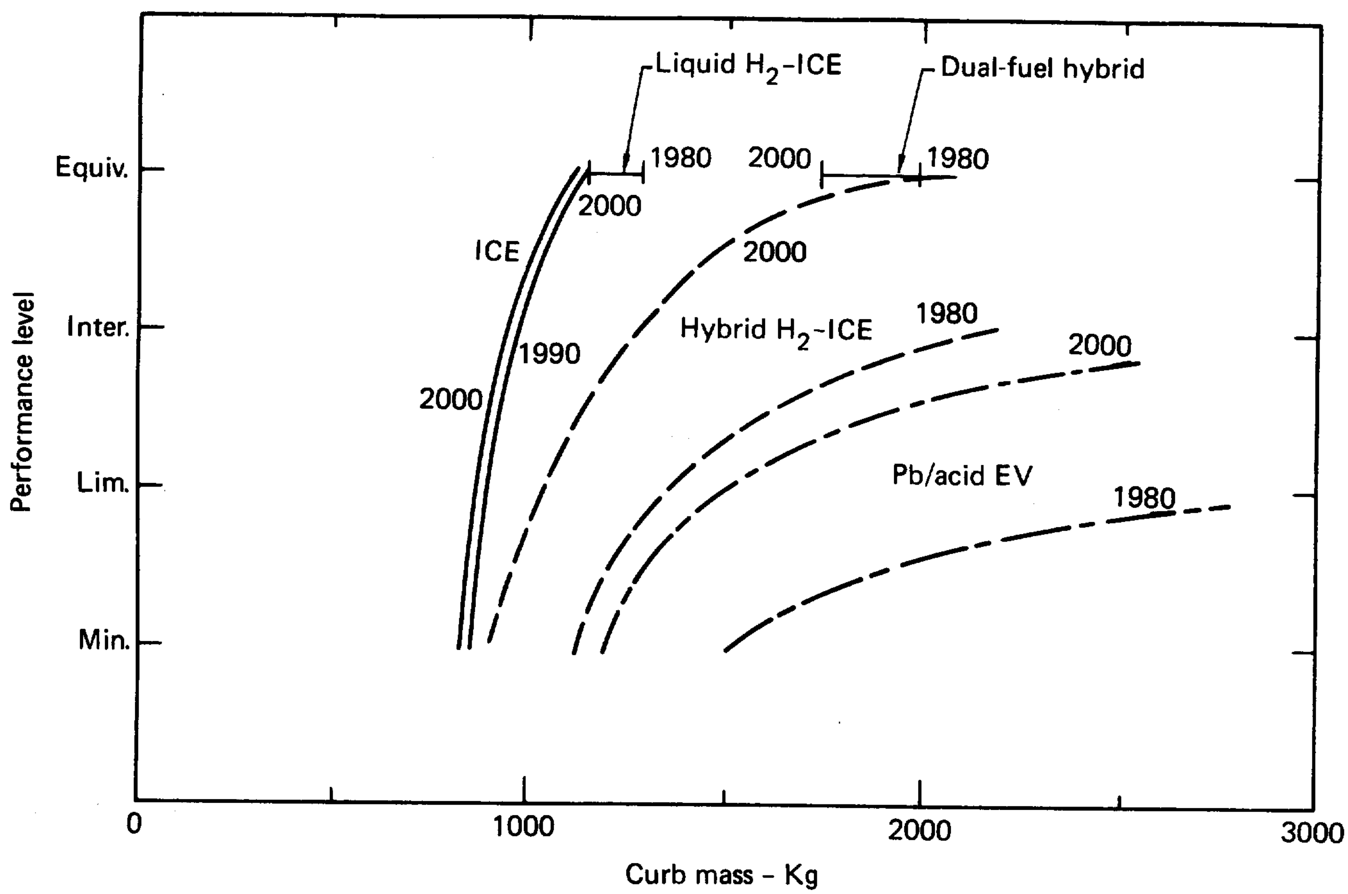


FIG. 32. Generalized relationship between vehicle performance and mass.

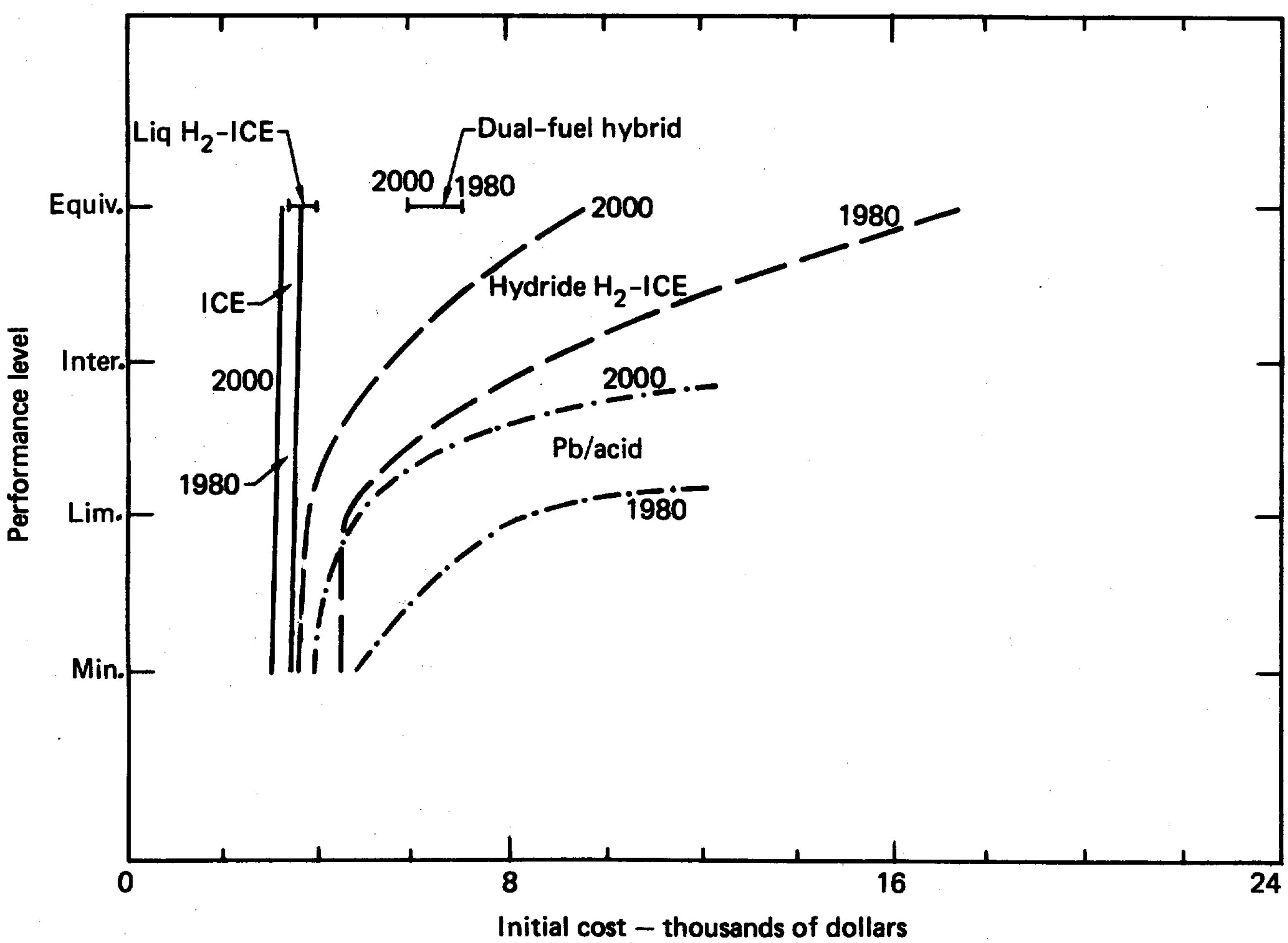


FIG. 33. Generalized relationship between vehicle performance and initial cost.

The battery/flywheel EVs parallel the all-battery EVs but at generally higher cost. A flywheel is capable of storing a relatively small amount of energy but able to supply high levels of power for short periods. Therefore the addition of a flywheel to any system in the battery-EV minimum or limited-performance category can significantly increase the system acceleration capability. This will only affect the mass/cost in the amount produced by reoptimizing the battery to a lower peak power, higher specific-energy configuration. Thus the addition of a flywheel or other power-boosting device to a lower-performance system is not reasonable except in the special case where a high-acceleration short-range vehicle is desired, such as for a commuter car. For the higher performance EVs and hybrids, a mechanical-energy-storage power-boosting device may be advantageous. This is true for the near-term battery systems where the weight and cost of battery capacity needed to reach the required acceleration levels may be much greater than the weight and cost of the booster system. This is examined in more depth in Volume 3 of the 1979 Study.

The hydrogen systems show cost superiority over the all-battery EVs except at the minimum performance level. Earlier in the study, cryogenic storage of hydrogen was evaluated, and although it projected very high energy densities and other superior properties, the system was set aside on the basis of envisioned safety problems. Figure 33, which shows only one of each type of system, indicates that the intermediate and limited range of performance is where the hydride-hydrogen systems show most promise. In the last time frame at high-performance levels the hydride-hydrogen systems appear to lose out in the projection to other systems. An inspection of the other hydride systems does not appear to conflict with this.

The dual-fueled hybrids vehicles (DFHV) are unusual. They owe their great value in the energy (petroleum) crisis to their use of electrical energy for the large majority of driving done at the rate of 80 to 120 km (50 to 75 mi) per day. With the ability to extend range by the use of a small, highly efficient ICE operating in a hybrid mode, a vehicle of equivalent performance is obtained. Although theoretically possible, no DFHVs were evaluated at other than equivalent performance. As early as the first time frame, a Pb/acid DFHV initial cost is projected to be less than any equivalent-performance vehicle other than the baseline ICE. DFHV are projected to have about the same costs as limited performance EV.

However, Figs. 28 to 31 show another part of the overall picture, the life-cycle costs (LCC). These figures indicate uniform operating costs for all these systems, at least until higher levels of performance are required. The DFHVs, however, remain competitive while providing equivalent performance. It must be recognized that petroleum availability and cost are extremely unstable and could easily affect this picture by 2000. Figure 34 simplifies these projections.

Three other systems were examined in this study. They are the thermal storage system, the power-leveling hybrid, and the powered roadway system.

The thermal-energy-storage system projected as about equivalent to improved near-term battery systems and was dropped from the study based on three critical factors. These included the state of development of the Stirling engine or other heat-engine design required for thermal energy propulsion, the problems and costs associated with recharging the thermal storage, and the safety of transporting the molten-salt storage and liquid-metal thermal-transfer system in a vehicle.

The power-leveling hybrids were considered by the End-Use Panel and results are reported in detail in Volume 2. These designs are all exclusively petroleum users, and the analyses show life-cycle costs equal to or slightly lower than the baseline ICE vehicle, but with generally increased initial costs.

Roadway power using inductive coupling is a relatively new concept and is described in the Volumes 2 of the Studies, but no End-Use analysis was possible at the current stage of development.

CONCLUSIONS

In summary, the three-year study of Energy Storage Systems for Automobile Propulsion has led to the following conclusions:

- Automotive energy-storage propulsion systems can be developed for various performance levels from general-purpose vehicles (ICE equivalent), such as dual-fueled hybrids, power-leveling hybrids, and hydrogen systems, to specific mission vehicles, particularly battery/flywheel electrics and all-battery electrics.
- No secondary battery system studied can be projected as first choice for development given the present state of the art and the uncertainties of

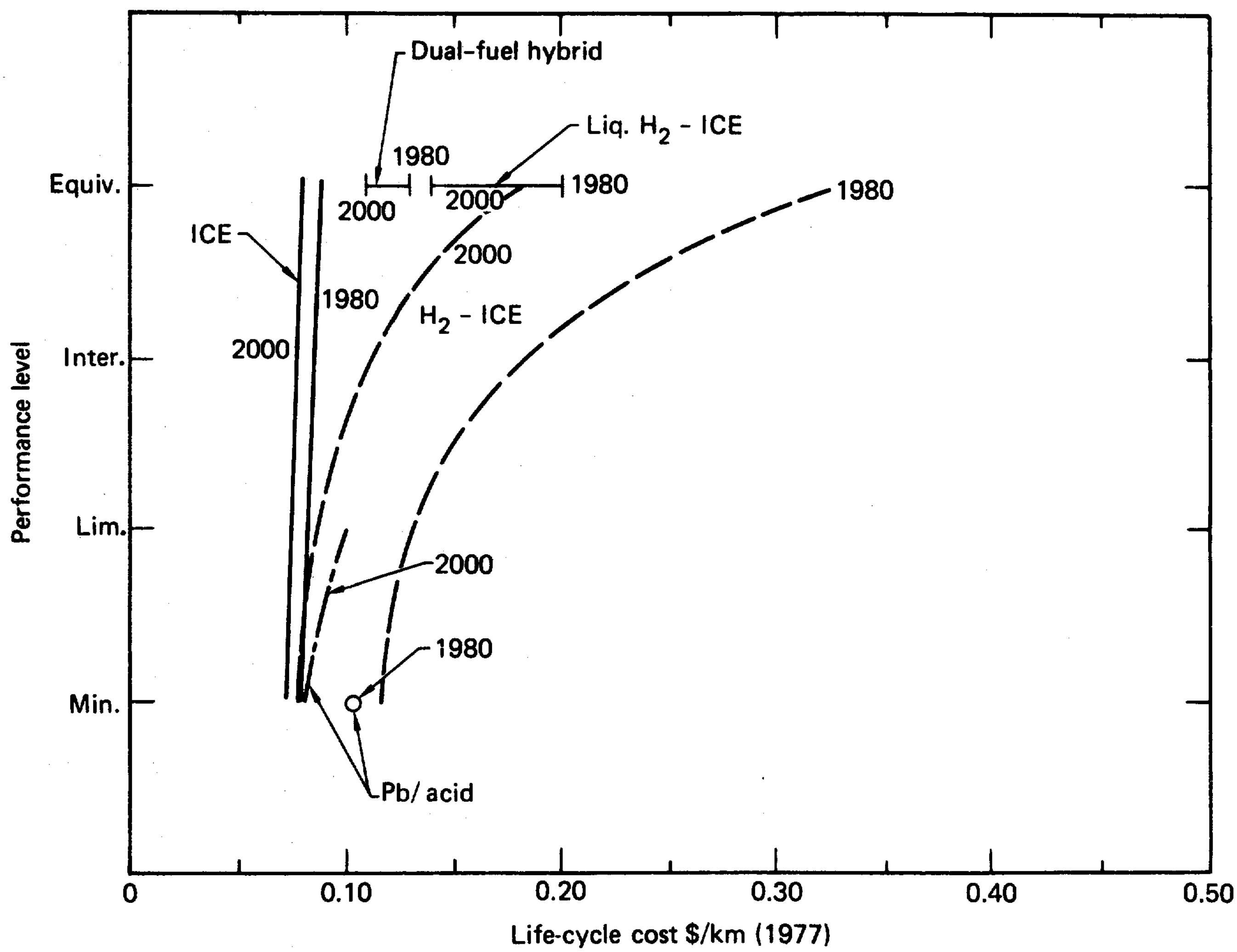


FIG. 34. Generalized relationship between vehicle performance and life-cycle cost.

future battery characteristics. Rapid refueling by battery exchange, the only way for secondary-battery EV to meet general purpose capability, does not appear to be feasible for general-use vehicles.

- All advanced energy-storage devices and vehicles are high risk developments.

- Near-term EVs are expected to achieve only minimum and limited performance.

- Most ESVs will weigh more and cost more than their ICE equivalents. The cost differential will decrease with time.

- If ESV performance is reduced, then these automobiles can be more cost competitive with today's ICE vehicles.

- The Pb/acid battery system is projected as having the lowest cost for minimum-performance EVs and for the dual-fueled hybrid vehicle (DFHV) near-term, equivalent-performance level. In later time periods, the advanced batteries allow better performance and also project lower initial and life cycle costs at the minimum and limited-performance levels.

- Flywheels or other mechanical-energy storage devices appear advantageous in higher performance EVs, where the cost of the battery capacity needed to reach the required acceleration levels may be much greater than the cost of the mechanical boost system.

- Hydrogen systems in general cost less than the all-battery EV's except at the minimum performance level. Liquid-hydrogen storage systems approach the ICE systems in initial cost at the equivalent-performance level, but have higher life-cycle costs.

- Dual-fueled hybrids are projected to provide vehicles of equivalent performance over all time periods, at costs comparable to limited-performance EV. However, petroleum costs and availability could seriously affect the status of DFHV.

- Although the projections of performance and cost for the exploratory Al/air battery system have a high degree of uncertainty at this tiime, the specific energy and rapid refueling capability are expected to make it the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles.

- Factors such as safety, supply problems, and infrastructure impose serious problems on several systems including thermal-energy storage and hydrogen systems, especially the cryogenic liquid system.

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